Transforming Systems Engineering through Model-Centric Engineering

Technical Report SERC-2018-TR-103

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EXECUTIVE SUMMARY

This is the final technical report of the Systems Engineering Research Center (SERC) research task RT-170. This research task (RT) addresses research needs extending prior efforts under RT-48/118/141/157 that informed us that Model-Centric Engineering[1] (MCE) is in use and adoption seems to be accelerating. Model-centric engineering can be characterized as an overarching digital engineering approach that integrates different model types with simulations, surrogates, systems and components at different levels of abstraction and fidelity across disciplines throughout the lifecycle. Industry is trending towards more integration of computational capabilities, models, software, hardware, platforms, and humans-in-the-loop. The integrated perspectives provide cross-domain views for rapid system level analysis allowing engineers from various disciplines using dynamic models and surrogates to support continuous and often virtual verification and validation for tradespace decisions in the face of changing mission needs.

NAVAIR senior leadership confirmed in late 2015 that NAVAIR must move quickly to keep pace with the other organizations that have adopted MCE and who continue to evolve at an accelerating pace enabled by the advances in computational and modeling technologies, and improved methods. In March of 2016, there was a Change of Command at AIR 4.0 (Research and Engineering) and NAVAIR leadership decided to accelerate the Systems Engineering Transformation (SET). During 2017 there was strategic planning to characterize the Functional Areas of the SET Execution Framework. One of those functional areas is the SET Research that is discussed in this report. This research provides analyses into NAVAIR enterprise capability, and builds on efforts for cross-domain model integration, model integrity, ontologies, semantic web technologies, multi-physics modeling, and model visualization that extend RT-157 research under RT-170 to address the evolving SET needs and priorities of SET.

A key decision by NAVAIR leadership in 2017 was to conduct a surrogate pilot as reflected in Figure 1. The aspects of this research task are blended into the surrogate pilot. The surrogate pilot is using experiments to simulate the execution of the new SET Framework, shown in Figure 2. The first phase of the SET Surrogate Pilot addresses the following mission, goals and objectives:

- **Mission:** Collaboration between Government and Industry in Model-based Acquisition under SET Framework
- **Goal:** Execute SET Framework to Assess, Refine, and Understand a New Paradigm for Collaboration in Authoritative Source of Truth (AST)
- **Objectives** (non-exhaustive):
  - Formalize experiments to answer questions about executing SET framework using Surrogate Contractor (SC)
  - ”Government team” creates mission, system (& other) models, “generates specification/Request For Proposal,” and provides acquisition models to SC as Government Furnished Information (GFI)
  - SC refines the GFI to make corrections and add innovations with physical allocation views with an multi-physics-based Initial Balanced Design

[1] DASD has increased the emphasis on using the term Digital Engineering (DE). A draft definition provided by the Defense Acquisition University (DAU) for DE is: **An integrated digital approach that uses authoritative sources of systems' data and models as a continuum across disciplines to support lifecycle activities from concept through disposal.** This definition is similar to working definition used throughout our prior research task (RT) 48/118/141 for Model Centric Engineering (MCE).

- Simulate continuous virtual reviews and derive new objective measures for assessing maturing design in AST
- Demonstrate visualizations for real-time collaboration in AST
- Demonstrate and document methods applied
- Investigate challenging areas and research topics in series of pilots

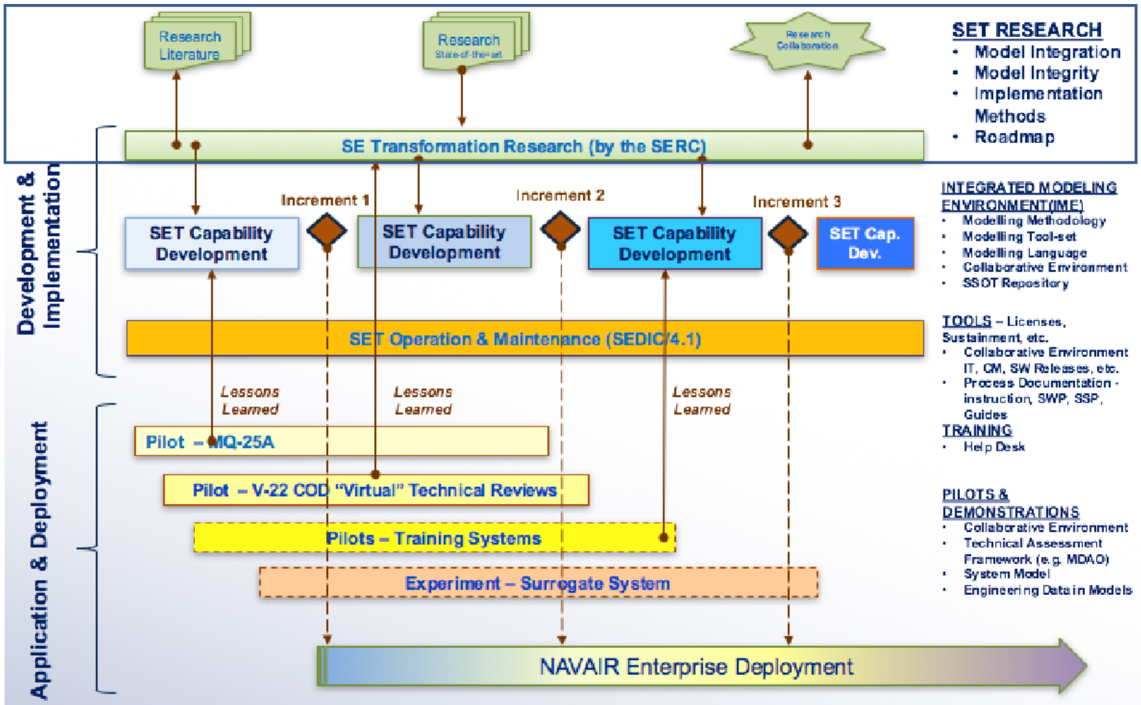

Figure 1. SE Transformation "Roll out" Strategy

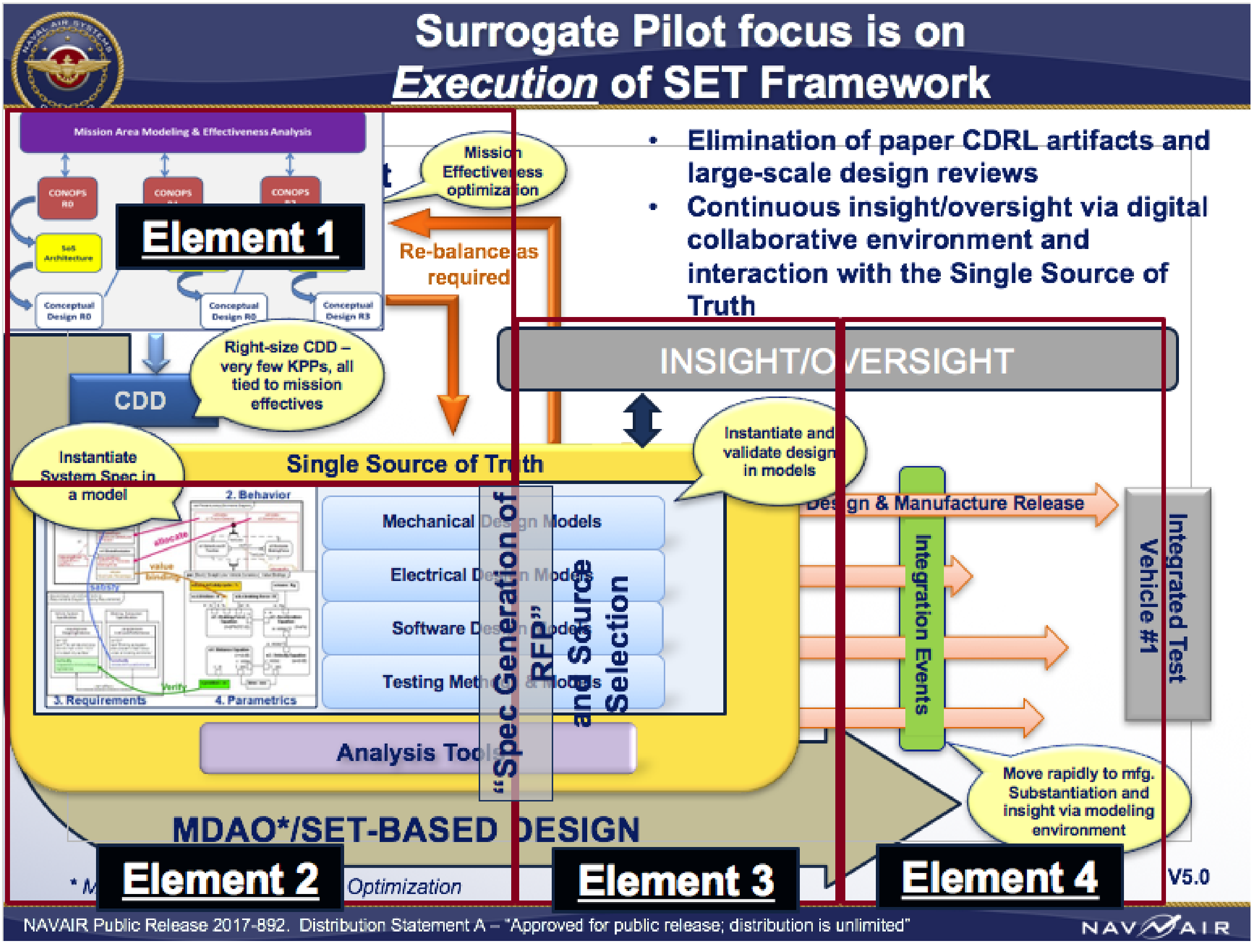

Figure 2. NAVAIR Systems Engineering Transformation Framework

While modeling everything may not be practical for all projects, the plan is to use models to the extent possible in order to demonstrate the feasibility and desired methods that will be captured as examples in reference models. The pilot is developing an experimental Unmanned Aerial Vehicle (UAV) system called Skyzer. The focus is on learning about a new operational paradigm between government and industry in the execution the SET Framework, not necessarily to produce an entire air vehicle design. There are many more detailed facets to the surrogate pilot that are discussed in this report, and the surrogate pilot, which had an official kickoff in December of 2017, is ongoing through 2018.

The strategic plans of SET and overarching goals of this research have been expanded through RT-170. RT-170 has research collaborators from Stevens Institute of Technology, Georgia Institute of Technology and University of Maryland, in addition to the surrogate pilot team that includes a Surrogate Contractor, and team members from NAVAIR and NAVAIR contractors. We are also working collaboratively with US Army RDECOM-ARDEC in Picatinny, NJ under RT-168, and some of the research results derived from those efforts that are being leveraged in the surrogate pilot are discussed in this report. We are also leveraging research efforts from RT-176, the Naval Postgraduate School Collaborators. Additional research associated with this research is planned for RT-195.

1 INTRODUCTION

In 2013, the Naval Air Systems Command (NAVAIR) at the Naval Air Station, Patuxent River, Maryland initiated research into a Vision held by NAVAIR's leadership to assess the technical feasibility of a radical transformation through a more holistic model-centric system engineering (MCSE) approach. The expected capability of such an approach would enable mission-based analysis and engineering that reduces the typical time by at least 25 percent from what is achieved today for large-scale air vehicle systems using a traditional document-centric approach. The research need included the evaluation of emerging system design through computer (i.e., digital) models.

Through Systems Engineering Research Center (SERC) research tasks (RT-48, 118, 141, 157) there was considerable emphasis on understanding the state-of-the-art through discussions with industry, government and academia [23] [35]. The team comprised of both NAVAIR and SERC researchers conducted over 30 discussions, including 21 on site, as well as several follow-up discussions on some of the identified challenge areas and approaches for a new operational paradigm between government and industry.

In 2015, the NAVAIR leadership concluded that they must move quickly to keep pace with the other organizations that have adopted MCE as the pace of evolution is accelerating by the enabling technologies. NAVAIR made the decision to press forward with a Systems Engineering Transformation (SET). That effort was started in January of 2016 under RT-157 and had four tasks as shown in Figure 3:

- Task 1 – Model Cross-Domain Integration with underlying Single Source of Technical Truth (SST)
- Task 2 – Model Integrity – developing and accessing trust in model and simulation predictions
- Task 3 – Modeling Methodologies aligning with the roll out of technologies defined under Task 4
- Task 4 – Define System Engineering Transformation Roadmap

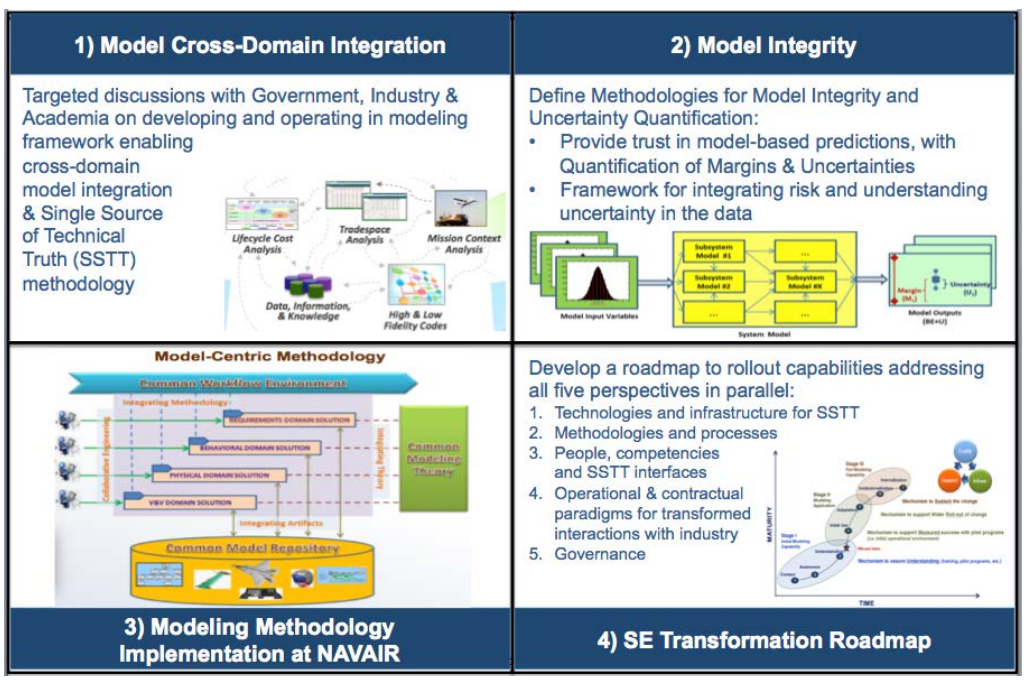

Figure 3. SE Transformation Phase II

In March of 2016, there was a Change of Command at AIR 4.0 (Research and Engineering). NAVAIR decided to accelerate the Systems Engineering Transformation (SET). Notionally as shown in Figure 4,

the research has a layered approach providing analyses into NAVAIR enterprise capability (e.g., modeling capabilities, reference models, and an authoritative source of truth), but builds on efforts for cross-domain model integration and model integrity (per RT-157). While the initial SERC research RT-48/118/141 was directed to focus on the Program of Record (POR)/systems level, a new NAVAIR strategy for accelerating capability delivery to the warfighter is looking to better assess the value and risks of system and system of systems (SoS) capabilities, potentially distributed across platforms to mission and campaign needs in a more dynamically changing environment. Therefore, NAVAIR added the following areas to the SERC research as characterized in RT-170, which are a layer on top of the other dimensions of the research, as shown in Figure 4:

- Prioritization and Trade-off Analysis
- Concept Engineering
- Architecture & Design Analysis
- Design & Test Reuse and Synthesis
- Active System Characterization
- Human-System Integration

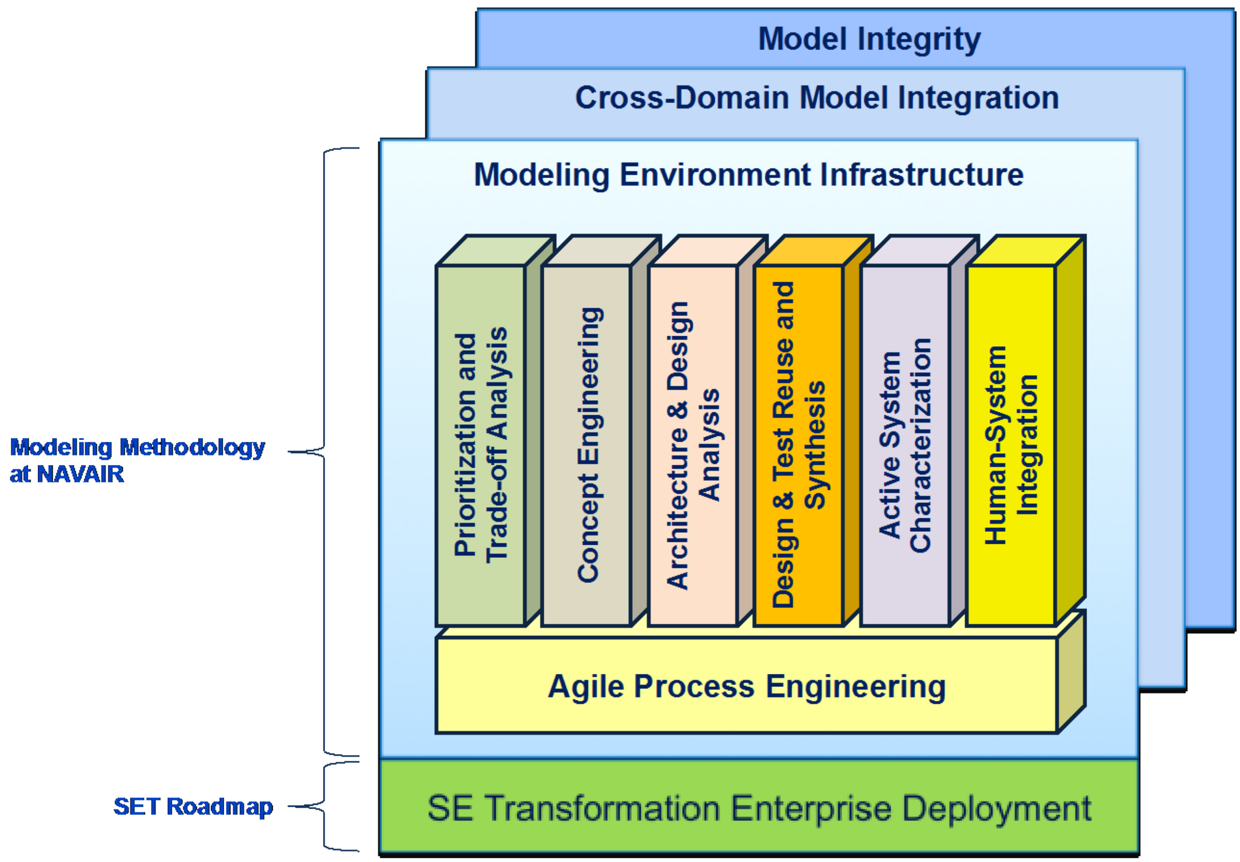

Figure 4. SE Transformation Research Areas (SERC)

During the execution of RT-157, our NAVAIR sponsor, Dave Cohen, proposed a new operational framework which has evolved into a concept depicted by Figure 2. The research efforts during 2017 for RT-170 started developing a surrogate pilot concept to assess and refine the Execution of SET Framework through a series of experiments. The emphasis is on a new operational paradigm to mission engineering, analysis and model-based acquisition, which would be led by NAVAIR with a collaborative design efforts led by industry. We continue to participate with our sponsors in industry meetings to assist in communicating and clarifying and aligning these concepts for a new type of collaboration, and

to assess the impacts on the NAVAIR enterprise, from both a technical and socio-technical perspective. Many objectives for assessment and refinement are characterized as objectives and captured as part of a Surrogate Pilot Project plan and model that will be traced to experimental models, demonstrations and results.

Briefly the concept of the new SET framework for transforming from a document-centric process with monolithic reviews to an event-driven model-centric approach involves, but is not limited to:

- A concept for collaborative involvement between Government and Industry to assess mission and System of Systems (SoS) capability analyses, where NAVAIR has the lead to:
  - Involve industry in SoS capabilities assessments during mission-level analysis (to the degree possible)
  - Iteratively perform tradespace analyses of the mission capabilities using approaches such as Multidisciplinary Design, Analysis and Optimization (MDAO) as a means to develop and verify a model-based specification
  - Synthesize an engineering concept system model characterized as a model-centric specification and associated contractual mechanism based on models or associated formalism
- At the contractual boundaries, industry will lead a process to satisfy the conceptual model addressing the Key Performance Parameters (KPPs), with particular focus on Performance, Availability, Affordability, and Airworthiness to create an Initial Balanced Design
  - Industry applies MDAO at the system and subsystem level too
  - There is a potential need to iterate back to re-balance the needs if the tradespace analyses of the solution/system for the program of record (POR) cannot achieve mission-level objectives
  - All requirements are tradeable if they do not add value to the mission-level KPPs
  - These are asynchronous activities in creating an Initial Balanced Design
  - Government and Industry must work together to assess “digital evidence” and “production feasibility”

Another objective under consideration in the context of the operational model is to replace large-scale document-centric reviews such as Systems Requirements Review (SRR), System Functional Review (SFR), Preliminary Design Review (PDR), etc. with continual event-driven reviews using objective evaluation based on model-centric information. NAVAIR needs some type of objective decision framework to assess evolving design maturity with considerations of value to the KPPs, risk and uncertainty. This is another objective for the surrogate pilot.

These efforts for improving the collaboration between government and industry are also underway to develop a new Concept of Operations (CONOPs) with organizations involved in the Aerospace Industry Association (AIA) working group [3], and the National Defense Industry Association (NDIA) Modeling and Simulation group which is looking at approaches for using digital engineering for competitive down select. We are involved in these efforts to further the objectives of our sponsor to communicate the SET Framework concept to industry and other Department of Defense stakeholders.

This report covers research performed against the RT-157 objectives, and at the request of our sponsor has expanded to address the needs of the SET under RT-170 using experiments in the Surrogate Pilot Project using a hypothetical system called Skyzer. Skyzer has a CONOPs for an UAV that provides humanitarian maritime support use cases as reflected in Figure 5. Another objective that must be factored into the use cases must allow the surrogate contractor to demonstrate measures to support a production-readiness decision for a multi-physics design.

Figure 5. Graphical CONOPS for Skyzer UAV

1.1 OBJECTIVES

The objectives of the research are cross-cutting and interrelated, as shown in Figure 6. The research needs expansion on the prior research and include specific focus on technological aspects to address the research gaps in the context of the SET Framework, but still include cross-domain model integration, model integrity, ontologies, semantic web technologies, modeling methods, multi-physics modeling, and model visualization. We summarize and organize the research in a manner used on RT-168 as use cases (UC) that cut across the evolving case studies as it relates to Figure 6.

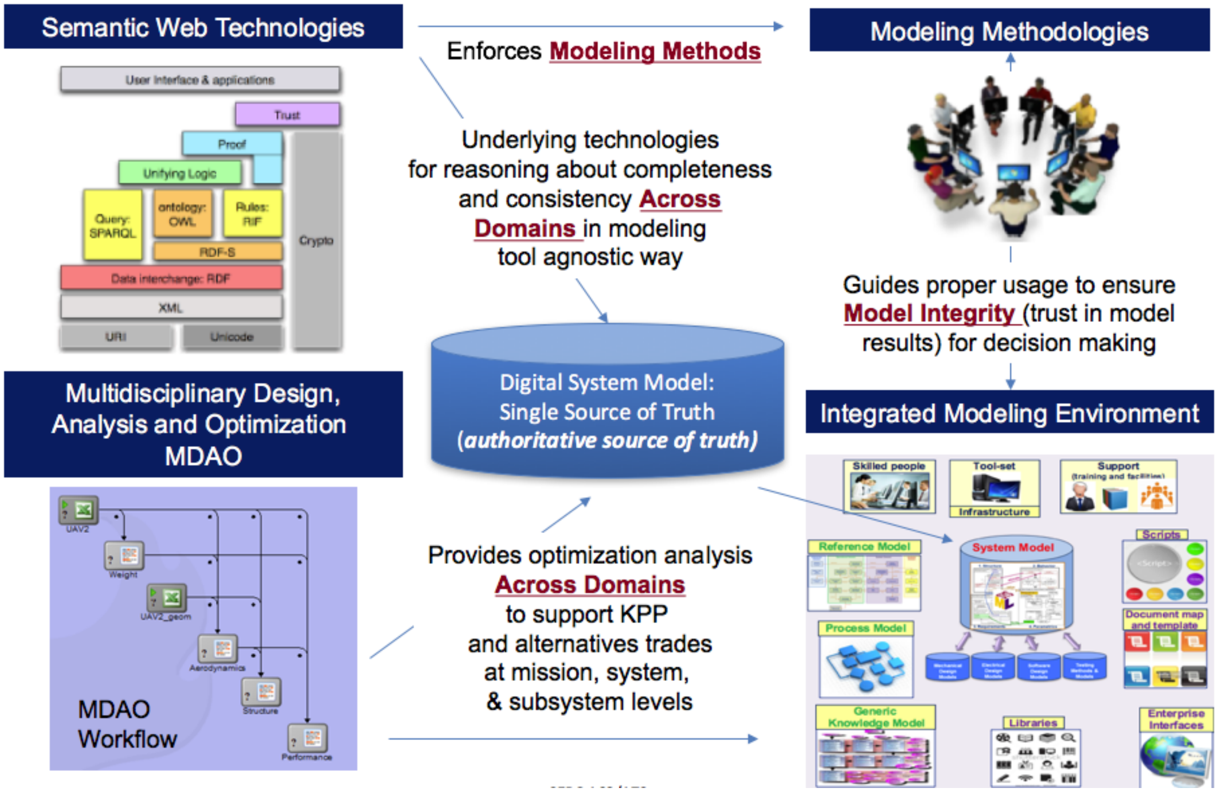

Figure 6. Cross-cutting Relationships of Research Needs

The use cases include, but are not limited to:

- UC00: Ontologies and semantic web technologies for reasoning about completeness and consistency across cross-domain model to achieve the notion of model integration through interoperability, which are enablers for an authoritative source of truth, tool-agnostic approaches to methodology enforcement and conformance that also support model integrity
- UC01: Multidisciplinary Design, Analysis and Optimization (MDAO) at the mission, system and subsystem levels, which provides a means for continual assessment of trades (i.e., analysis of alternatives) to support KPP assessment; this also relates to representations within system models
- UC02: Integrated Modeling Environment (IME) in the context of the workflows, which has implications on both technologies and workforce development
  - We are using an instantiation of OpenMBEE [118] as the experimental integrated modeling environment formalization of the AST, in the context of NAVAIR, but also in the context of one or more industry contractors
  - Model visualization from multiple perspectives including, but not limited to enabling different views relevant to different stakeholder (or due to particular access), reducing complexity, and analytical analysis
  - Methods for model modularization to ensure separation of concerns, classification, and acquisition
  - Methods for creating and organizing Enterprise, Process, and Reference models
  - Understanding the operational paradigm between industry and government in the context of the SET Framework through MCE

- Workflow analysis and representation relative to a program instantiation of tool suites from the IME
    - NOTE: cybersecurity and classification is not currently in the scope of this work
- UC03: Methodologies relevant to technologies in the context of the IME workflows, such as:
    - Methods for system model
    - Methods for mission model
    - Methods for MDAO modeling
    - Methods for modularizing models to support constraints needed for developing an Authoritative Source of Truth (AST), which relates to many other use cases
    - Methods for model management
    - Methods for representing and organizing reference models, process models, discipline-specific models
    - Methods for developing and tracing capabilities measure to KPPs
    - Alternative approaches to improve modeling methods, which is fundamental to ensuring model integrity (strong relationships to UC02)
- UC04: Model-physics modeling, which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty
- UC05: Representation to formalize research under RT-176 in models to support requirement verification and validation using Monterey Phoenix
- UC06: Experimentation and learning about defined research topics in the execution of the SET through unclassified pilot programs, such as the SET Surrogate Pilot; this includes alignment with the SET Tasking and other research use cases with evolving pilot case studies (as described below)
- UC07: Research into Enterprise Transformation to support governance and workforce development (not covered in this report; initial funding is included under RT-195)

1.2 Scope

The scope for the research aligns the objectives as characterized by the use cases in Section 1.1 to the prioritizes of the SET in the context of the surrogate pilot for experimenting with the research to produce models and demonstrations for NAVAIR-relevant examples that can help inform the workforce and other stakeholders. These objectives include, but are not limited to understanding the methods, models, tools and processes to execute the SET Framework.

The two perspectives that are further described throughout this report can be thought of as overarching use cases, as reflected by Figure 7:

1. Use cases about the objectives for the Skyzer experiments and associated environments:
    - Surrogate Pilot Use Cases characterize objectives for understanding the execution of the SET Framework
        - A non-exhaustive set of objectives for the surrogate pilot are characterized in the SET Surrogate Pilot Project Model; an automatically generated version of the model content (e.g., “document”) from this evolving model is provided in Section 3
    - Collaboration in an Authoritative Source of Truth (AST) Use Cases
        - The government side of the AST is being developed using the NASA/JPL OpenMBEE [118] and commercial modeling tools that is hosted on Amazon Web Services server
        - The surrogate contractor side of the AST must be “integrated” with the government side of the AST

2. Use cases for the Skyzer Experimental System using AST, which involves the development of evolving models for:
    - o Surrogate Project/Planning Model
        - Characterizes the objectives for the surrogate pilot and research
        - Discussed in more detail in this report in Section 3
    - o Project Planning for Skyzer
        - Currently this is a more traditional document
    - o Mission Model for Skyzer
        - Parts of mission model provided as Government Furnished Information (GFI)
        - Primarily associated with Element 1 of SET Framework
    - o System Model for Skyzer
        - Parts of system model provided as GFI
        - Primarily associated with Element 2 of the SET Framework
    - o Acquisition Model Skyzer
        - Primarily associated with boundary between Element 2 and Element 3 of the SET Framework
        - Provide criteria for source selection evaluation
    - o Surrogate Contractor System model for Skyzer
        - Surrogate contractor to assess, refine and extend GFI system model
        - Primarily associated with Element 3 of the SET Framework
    - o Surrogate Contractor Design models for Skyzer
        - Design models much address aspects of multi-physics
        - Primarily associated with Element 3 and Element 4 of the SET Framework
    - o View and Viewpoints for DocGen and other Libraries

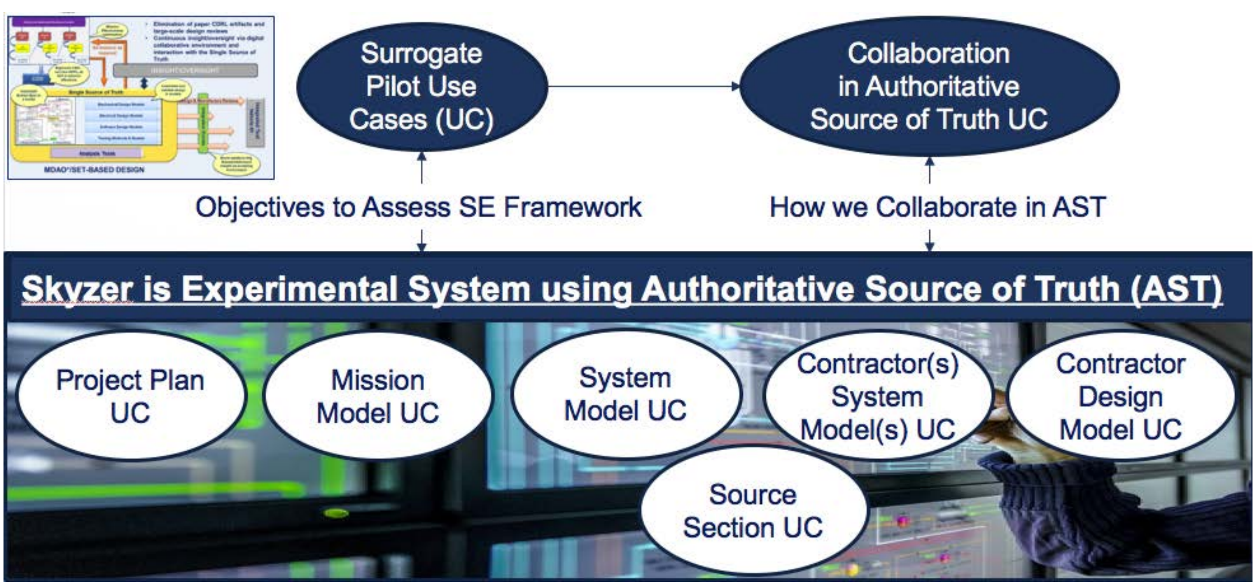

Figure 7. Use Cases for Surrogate Pilot and Experimental System (Skyzer)

As shown in Figure 8, this concept involves developing operational models and user capabilities, which are primarily defined in the Skyzer Mission Model. The mission model(s) provides inputs that are captured in an “Initial System Model” that characterizes the “requirements” derived from models that will be part of a Request for Proposal (RFP) that would be elaborated by contractors during source

selection into a "Final System Model." This model is the Skyzer System Model and being developed by our Georgia Tech collaborator. We are simulating this concept during the pilots. Notionally, Figure 8 shows the related alignment to the four Elements 1, 2, 3, & 4 with the focus being on formalizing SET using models.

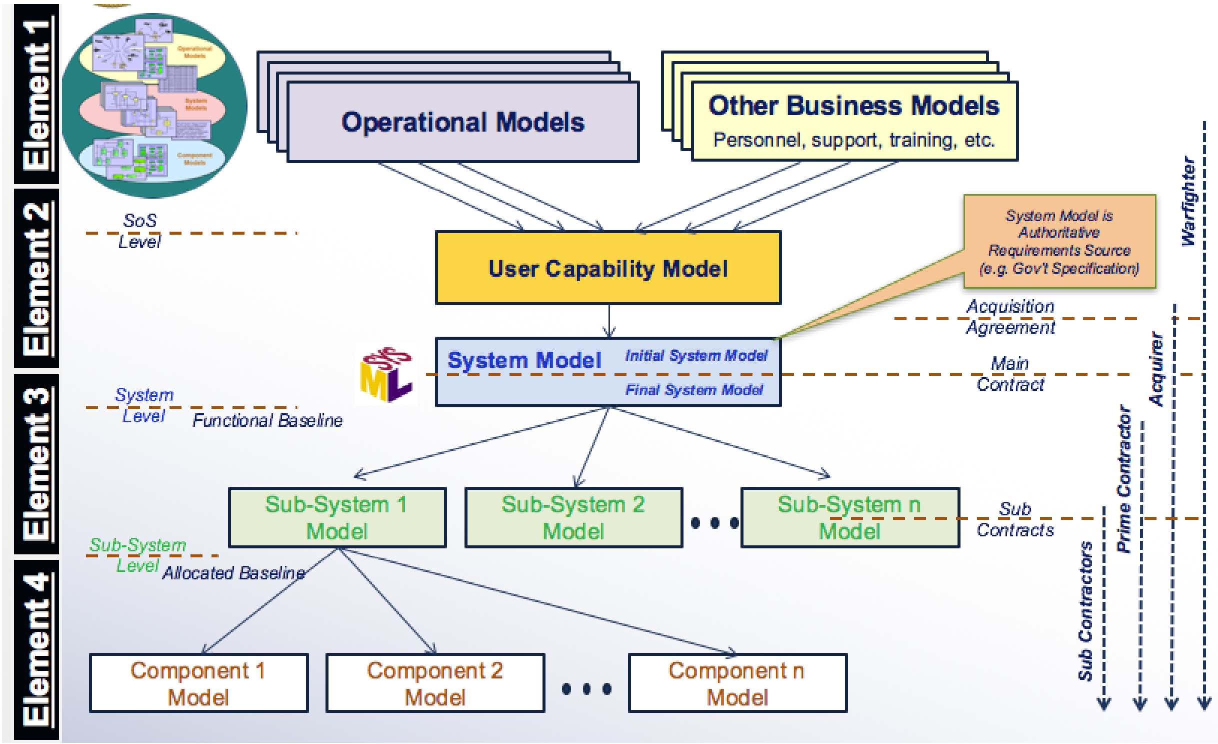

Figure 8. Characterizes the Boundary of Models between Government and Industry

The research approach will use experimentation in evolving pilot project scenarios to help inform the workforce, as well as create reference models as examples to exemplify best practice methods. Our research is already investigating concepts that have never been attempted by NAVAIR. There are many questions that have surfaced related to the execution of the SET Framework, and we cannot address all of these during the surrogate pilot, but reflect on some of the broad needs, for example:

- Simulating Mission Engineering and Analysis (Element 1) and System modeling (Element 2) prior to contract award
- Formalization/synthesizing a "specification" from models for "RFP" and methods for providing models to contractor
- Simulating "Execution" of Oversight / Insight in a Single Source of Truth per SET Framework and capturing abstractions of "recommended" processes in potentially heterogeneous environments (Elements 3 & 4)
- Developing and assessing the use of objective measures for evaluating evolving design maturity, while assessing the reduction of risk and uncertainty
- Simulating feedback back to mission engineering caused by specified objectives for unachievable KPP
- Simulating approach for "faults in specification/model" detected after contract award to look at the potential needs for a new paradigm referred to as model-based acquisition
- Simulating source selection and investigate if it is possible to use dynamic simulations and V&V as part of the source selection process and evaluation criteria

- Working with contracts/legal to get agreement on what a “specification” would or can be, while helping to understand potential needs to change acquisition policy
- Methods for modularizing model used to “generate specification” and for sharing digital models while addressing access needs such as security
- Assessing how or if we can use an ontological representation of the Systems Engineering Technical Review (SETR) guide and checklist that NAVAIR uses? And, how will we make recommendations for its evolution in the context of MCE
- Use of Multidisciplinary Design, Analysis and Optimization

1.3 COLLABORATIVE RESEARCH SYNERGIES

Finally, NAVAIR is also involved in synergistic collaborative efforts with ARDEC and the Digital Engineering (DE) Working Group led by ODASD(SE), and we are working to align the research, to the extent possible, with the five DE Transformation goals that include:

- G1. Formalize the development, integration and use of models to inform enterprise and program decision making.
- G2. Provide an enduring authoritative source of truth.
- G3. Incorporate technological innovation to link digital models of the actual system with the physical system in the real world.
- G4. Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.
- G5. Transform a culture and workforce that adopts and supports Digital Engineering across the lifecycle.

As is reflected in Figure 9, many of the research topics under investigation by the SET align with the DE Transformation goals. In addition, the mapping in Figure 9 shows that the research areas have significant overlap with some of the DE goals. This means that in order to achieve some of the goals, it will be necessary to have successful research outcomes across many research areas. Therefore, in the Part II of this report, the research areas are defined as cross-cutting use cases rather than specific tasks, which is similar to what evolved out of the RT-168 research task with ARDEC.

Future Research Areas	G1. Formalize the development, integration and use of models to inform enterprise and program decision making.	G2. Provide an enduring authoritative source of truth.	G3. Incorporate technological innovation to link digital models of the actual system with the physical system in the real world.	G4. Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.	G5. Transform a culture and workforce that adopts and supports DE across the lifecycle.
Cross-discipline integration of models to address the heterogeneity of the various tools and environments using semantic technology	X	X	X	X	X
High Performance Computing (HPC) advancements such as; 1) supporting organizing and analyzing "Big Data" and 2) being able to program in parallel to take advantage of HPC capabilities, are needed to support the DE effort	X	X	X	X	
Model integrity to ensure trust in the model predictions by understanding and quantifying margins and uncertainty	X	X	X	X	X
Modeling methodologies that can embed demonstrated best practices and provide computational technologies for real-time training within digital engineering environments	X		X	X	X
Model composability to understand the possibilities, constraints and rulesets for composition of multiple models	X		X		
Human-model task allocation to understand what activities are best performed by human decision makers and what can effectively be automated or augmented with model intelligence					X
Workforce development to understand what is needed to educate model developers, users and decision makers to work in a DE environment					X
MCE acquisition to understand the needed changes to acquisition and security when developing in the new DE environment	X	X		X	X

Figure 9. Future Research Areas Mapped to Goals of Digital Engineering Transformation Strategy

These use cases will investigate continuing synergistic research with the US Army ARDEC under RT-168, Semantic Technologies for Systems Engineering (ST4SE) initiative, RT-176 and other potential SERC research that is aligned with the principles and concepts for the SET as well as the ODASD(SE) Digital Engineering Strategy.

1.4 Organization of Document

Section 1 provides an overview of the context for the needed research, objectives, expanded scope and organization of this report.

Section 2 provides a summary of our efforts, meetings, and deliverables.

Section 3 includes a unique approach to the creation of Section 3, which is automatically generated from SET Framework Surrogate Project model. We include this section to illustrates the capabilities to leverage models and with the OpenMBEE Model Development Kit (MDK) DocGen capabilities.

Section 4 describes the use case that investigates the development and use of ontologies and more generally semantic web technologies (SWT) for reasoning about completeness and consistency across

cross-domain models. These capabilities support enforcement of modeling methods and support for model integration through interoperability.

Section 5 describes the use case that investigates various uses of Multidisciplinary Design, Analysis and Optimization (MDAO) at the mission, system and subsystem levels, which provides a means for continual assessment of trades (i.e., analysis of alternatives). This section also discusses methods for applying MDAO, and a modeling approach that allows SysML models to be transformed into MDAO workflows.

Section 6 describes the use case that investigates topics for Integrated Modeling Environments (IMEs) with specific focus on creating and collaborating in an AST for the surrogate pilot in the context of the research thrusts, and the specific instantiation of the IME that is being used for the surrogate pilot.

Section 7 discusses the use case that investigates the development and demonstrations of methods for mission, systems, model modularization and management for technologies in the context of the IME workflows.

Section 8 discusses the use case that investigates model-physics modeling, MDAO and model integrity which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty.

Section 9 discusses the use case that investigates the development of SysML representations to formalize the Monterey Phoenix research under RT-176 support requirement verification and validation.

Section 10 discusses the use case that defines the objectives for experimentation and learning in the execution of the SET, which is related to surrogate pilot plan and model described in Section 3.

Section 11 is a placeholder for a task that is to be funded under RT-195 for Enterprise Transformation to support governance and workforce development.

Section 12 summarizes some of the SERC research synergies.

Section 13 provides a summary and some conclusions.

2 RESEARCH EVENTS AND DELIVERABLES SUMMARY

This section provides a high-level summary of the research-related events, results and deliverables. Unlike prior final reports, we are not including a historical perspective of prior research, but have shifted focus to the recent developments in 2017 for the SET, with specific focus on the research addressed through the surrogate pilot. The technical reports RT-141 [23] and RT-157 [29] provide a comprehensive summary and historical perspectives leading up to the SET.

Part II of this report includes a summary of the Surrogate Pilot Project that is the venue in which we work on the cross-cutting research. Section 3 has been automatically generated from the SET Framework Surrogate Project model and provides significant details on the surrogate pilot. In addition, Part II provides details on each use case, as well as the research synergies leveraged from the ARDEC research under RT-168 [26].

2.1 WORKING SESSIONS AND SPONSOR-SUPPORTING EVENTS

A component of the research and required deliverables are conducting working sessions that inform the NAVAIR team about progress against the plan. These working sessions also inform the team about relevant information and feedback to scope the deliverables in the context appropriate for NAVAIR; this has been especially important given the recent changes under SET. We also use bi-weekly drumbeats to share status and updates. Each working session has a defined agenda, and detailed meeting notes are provided to our sponsor. The following provides a summary of the working sessions and other events, and a brief description of the contributions to the tasks and deliverables.

- Participation in Bi-weekly Drumbeat
- Working session at NAVAIR February 2, 2017
- Working session at NAVAIR March 9, 2017
- Special session to discuss SET at Northrop Grumman, El Segundo, CA with Dave Cohen, Jaime Guerrero and David Meiser, March 14, 2017
- Special session to discuss SET at NASA/JPL, Pasadena, CA with Dave Cohen, Jaime Guerrero and David Meiser, April 20, 2017
- Special session to discuss SET at Lockheed Martin, Ft. Worth, TX with Dave Cohen, Jaime Guerrero and David Meiser, April 20, 2017
- Working session at NAVAIR May 4, 2017
- Working session at NAVAIR June 8, 2017
- Working session and pre-meeting on surrogate pilot at NAVAIR July 12 & 13, 2017
- Working session and follow-up meeting at NAVAIR, August 16 & 17, 2017
- Working session and follow-up meeting at NAVAIR, September 19 & 20, 2017
    - Official Kickoff of the NAVAIR SE Transformation by Dave Cohen on September 19
- Special Briefing of the SET with Kristin Baldwin, Jim Thompson, Phil Zimmerman, Tracee Gilbert, and Jared Kaib at NAVAIR, October 2, 2017 with Dave Cohen, Jaime Guerrero and David Meiser
- Working session at NAVAIR October 19, 2017
- Working session at NAVAIR November 16, 2017
- Surrogate Pilot Kickoff at NAVAIR December 7, 2017 with Dave Cohen, Jaime Guerrero and David Meiser
- Conducting weekly meetings with Surrogate Contractor and Surrogate Pilot Team, which started December 2017; updates on meeting in All Partners Access Network (APAN)
- Working session at NAVAIR January 25, 2018

Other related NAVAIR/SERC events:

- Attended NASA/JPL Symposium and Workshop on Model Based Systems Engineering, January 25-27; there is a separate report that covers the entire event
- Attended INCOSE International Workshop, January 28-31, 2017; there is a separate report that covers this event
- Helped with pilot MAGTF Agile Networking Gateway Link (MANGL) Overview for MBSE; collaborate with John Funk
- MBSE/SysML workforce training supported by Georgia Tech
- Semantic Technology for Systems Engineering (ST4SE); Dinesh Verma initiated an effort with the support of Chi Lin, Steve Jenkins and Mark Blackburn to bring a community of people together in an attempt to create and ecosystem on Semantic Web Technologies
  - Started with a meeting was held at NASA JPL on March 22nd on the subject
  - Core ST4SE team general meets bi-weekly and there have been three face-to-face meetings
- Bi-weekly participation in the Open Collaboration Group for MBSE that is providing support for adopting and contributing to OpenMBEE
  - This was critical to our success in deploying OpenMBEE for the Surrogate Pilot
- We are participating in the Aerospace Industry Association (AIA) CONOPS for MBSE Collaboration
  - This is a follow-up to the effort completed last year which developed a white paper on the Life Cycle Benefits of Collaborative MBSE Use for Early Requirements Development [3]
  - We have informed many industry providers to NAVAIR about the Surrogate Pilot
- Meeting NASA/JPL with Dave Cohen, Jaime Guerrero, David Meiser and Mark Blackburn to discuss concept of SET with NASA/JPL team and understand NASA's use of MCE on projects such as Europa and Asteroid Rendezvous & Retrieval Mission projects
- Industry meetings with Dave Cohen, Jaime Guerrero, David Meiser and Mark Blackburn to discuss new operational paradigm for executing against SET between industry and government
- Involved in collaboration with RT-176, called Verification and Validation (V&V) of System Behavior Specifications. Jaime Guerrero wanted to ensure that RT-176 aligns with the objectives from RT-157 and RT-170 and asked Mark Blackburn to be involved in RT-176 as a Co-PI
- Special Session: 31-July-2017 held at Stevens Institute of Technology
  - This special session invited our sponsors from ARDEC, NAVAR, and DASD(SE), but also other organization Naval Surface Warfare Center, Digital Warfare Office, and MITRE, and industry guests from Raytheon working on Semantic Web Technologies and Ontologies
  - Objectives included: "Provide Big Picture – Mental Model"
  - "Past – Why" – Historical perspectives – How we got here and why
  - "Present – What" - Aligning the research gaps and challenges for a Systems Engineering Transformation
  - "Future – How" - Blending and evolving our research results with Digital Engineering (DE) Transformations across the Department of Defense (DoD) to be in a Future State by Computationally Enabled DE
  - Deep Dive a Few Research Topics
  - Integrated Systems Engineering Decision Management (ISEDM) Process Enabled by Digital Engineering Technologies, presented by Dr. Matthew Cilli
  - Semantic Technologies and Ontologies Research to enable Trade Space Analytics for Engineered Resilient Systems, presented by Dr. George Ball
  - Breakout Session discussing
    - Risk for Digital Engineering Transformation

- Priorities for Digital Engineering Transformation

- National Defense Industry Association (NDIA) - presented Surrogate Pilot Overview, October 25, 2017
- SERC Sponsor Research Review (SSRR) – presented Surrogate Pilot Overview, November 8, 2017
- Ontology Boot Camp sponsored by SERC on December 5, 2017

2.2 Deliverables

As required by the contract, we produced:

- Technical Management and Work Plan
- Interim Technical Report
- Bi-monthly status reports
- Meeting Notes and Briefings
- Final Technical Report

We have also produced models, demonstrations, videos, examples and assembled tools for an Integrated Modeling Environment (IME) for the surrogate pilot. The following provides a list of models that have been produced and supplied to NAVAIR:

- APAN (apan.org)
  - Tracking progress of the surrogate pilot using Discussion group that is linked to related evolving artifacts
  - Posting documents into both the general NAVAIR SET area as well as the Research area
- Successfully created instantiation of OpenMBEE both at Stevens and on Amazon Web Services (AWS) to be used in the surrogate pilot
- Demonstration of OpenMBEE Model Development Kit (MDK)/DocGen
- Surrogate Project Plan Model
- Surrogate Mission Model for Skyzer
- Surrogate System Model for Skyzer
- Skyzer Request for Information package
- Briefing on creating SysML Activity Diagram for Monterey Phoenix in support of RT-176
- MDAO demonstrations
- Videos for the operations of OpenMBEE with Teamwork Cloud to be used on surrogate pilot
- SysML one-day course that is provided by Stevens Institute of Technology for the SYS-671,672,673,674 Cyber Physical Systems course

Part II: Task Detail Summary

Part II includes a unique approach to the creation of Section 3, which has been automatically generated from SET Framework Surrogate Project model, and then inserted into this report. We include this section to illustrates the capabilities to leverage models with the OpenMBEE Model Development Kit (MDK) DocGen capabilities. The Document Generator (DocGen) is a module of MDK plug-in in MagicDraw. It provides the capability to generate formal documents from UML/SysML models in MagicDraw. A "document" is a view into a model, or a representation of model data, which may be structured in a hierarchical way. We are able to produce information extracted from that model using View and Viewpoints [118]. It is included here to provide examples of the types of research we are conducting and to provide an example to illustrate that it is possible to completely develop “documentation” and “specifications” using models and associated modeling technologies like DocGen. Note also the figure and table number comes directly from the generation process. The latest updates will be available from the Amazon Web Service which is hosting OpenMBEE and the surrogate pilot models or on APAN [7]. The only modifications that we made to the generated content in Section 3 is to use the standard SERC Heading styles in this report and to resize the figures.

The remainder of the sections provides additional details associated with the research use cases listed in Section 1.1. An extensive amount of material covered in Part II of the RT-141 final report [23] and RT-157 final report [29] is still relevant information to this research, but has not been included in this report. For the convenience of the readers, we include some of the key topics from those reports:

- Traceability and scope of data collection of state-of-the-art MCE relevant topics collected from global scan of industry, government and academic
- Characterization of canonical reference architecture of an Integrated MCE Environment
- Model cross-domain integration within the underlying single source of truth
    - Information Model for a Single Source of Technical Truth
    - Requirement ontology
    - This topic is still relevant and discussed in this report
- Model Integrity – developing and accessing trust in model and simulation predictions
- Modeling methodologies
- Multidisciplinary Design, Analysis and Optimization (MDAO)
- Example models
- Modeling and Methods for Uncertainty Quantification
    - Dakota Sensitivity Analysis and Uncertainty Quantification (UQ)
    - Overview of Quantification of Margins and Uncertainty
- Modeling Methods for Risk
- Controlled Natural Language Requirements information
- Cross-Domain Integration and Natural Language Process of Requirements using Ontologies

3 NAVAIR - SERC Systems Engineering Transformation Surrogate Pilot

3.1 SE Transformation Surrogate Pilot Project

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Tue Jan 30 11:38:07 EST 2018

3.2 Chapter 1. Surrogate Pilot Overview

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This is a work in progress. This document was completely generated from a combination of models as described in this document.

The purpose of this project is to simulate the ***Execution*** of the new Systems Engineering Transformation (SET) Framework using a "completely" model-centric approach. Therefore, while modeling everything may not be practical for all projects, the plan is to attempt to use models exclusively in order to demonstrate the feasibility and desired approaches that will be captured in reference models. The current model defines the first phase of the Surrogate Pilot.

Mission: Collaboration between Government and Industry in Model-based Acquisition under SET Framework

Goal: Execute SET Framework to Assess, Refine, and Understand a New Paradigm for Collaboration in Authoritative Source of Truth (AST)

Objectives (non exhaustive - see Surrogate Pilot Objectives):

- Formalize experiment to answer questions about executing SET framework using Surrogate Contractor (SC)
- ”Government team” creates mission, system (& other) models, “generates specification/RFP,” & provides acquisition models to SC as Government Furnished Information (GFI)
- SC refines GFI reflects corrections/innovations with physical allocation views with multi-physics-based Initial Balanced Design
- Simulate continuous virtual reviews and derive new objective measures for assessing maturing design in AST
- Demonstrate visualizations for real-time collaboration in AST
- Demonstrate and document methods applied
- Investigate challenging areas and research topics in series of pilots

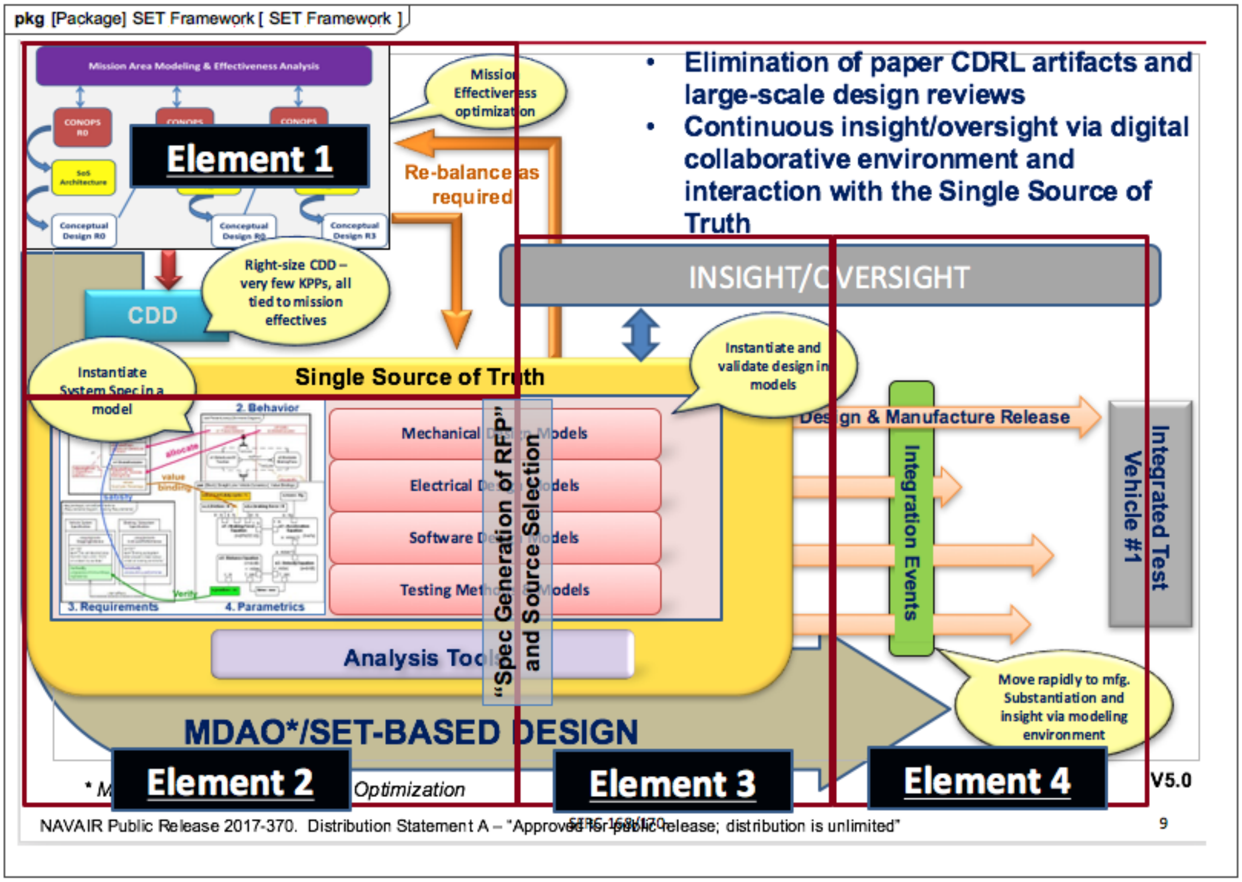
The main components of this model are shown from different views to include:

1. **The Surrogate Project/Planning Model (this component)**
2. The Project Planning Model for Skyzer
3. Surrogate Mission Model for Skyzer
4. Surrogate System Model for Skyzer
5. Surrogate Acquisition Model Skyzer
6. View and Viewpoints for DocGen and other Libraries

We focus on learning about a new operational paradigm between government and industry in the Execution the SET Framework (NOT an air vehicle design). There are many more detailed facets to the surrogate pilot. The following is a non-exhaustive list of examples that are formalized as mission objectives for the surrogate pilot using a model:

- Simulating prior to contract award
- Formalization of a “specification” for “RFP” and methods for providing models to contractor
- Simulating “Execution” of Oversight / Insight in AST per SET Framework for real-time collaboration in heterogeneous environments
- Objective measures for evaluating evolving design maturity, with the reduction of risk
- Simulating feedback back to mission engineering caused by specified objectives for unachievable KPP
- Simulating approach for “faults in specification/model” detected after contract award
- Simulating source selection – desirably as a dynamic simulations and V&V
- Working with contracts/legal to get agreement on what a “specification” would be
- Methods for modularizing model used to “generate specification”
- How will we use the SETR guide and checklist that NAVAIR uses? And, how will we make recommendations for its evolution
- Applying research concepts such as:
    - Cross-domain model integration
    - Model integrity
    - Ontologies and semantic web technology
    - Use of Multidisciplinary Design, Analysis and Optimization (MDAO)
    - Modeling methods
    - Demonstrations bring this research together using OpenMBEE

Figure 1.1. SET Framework



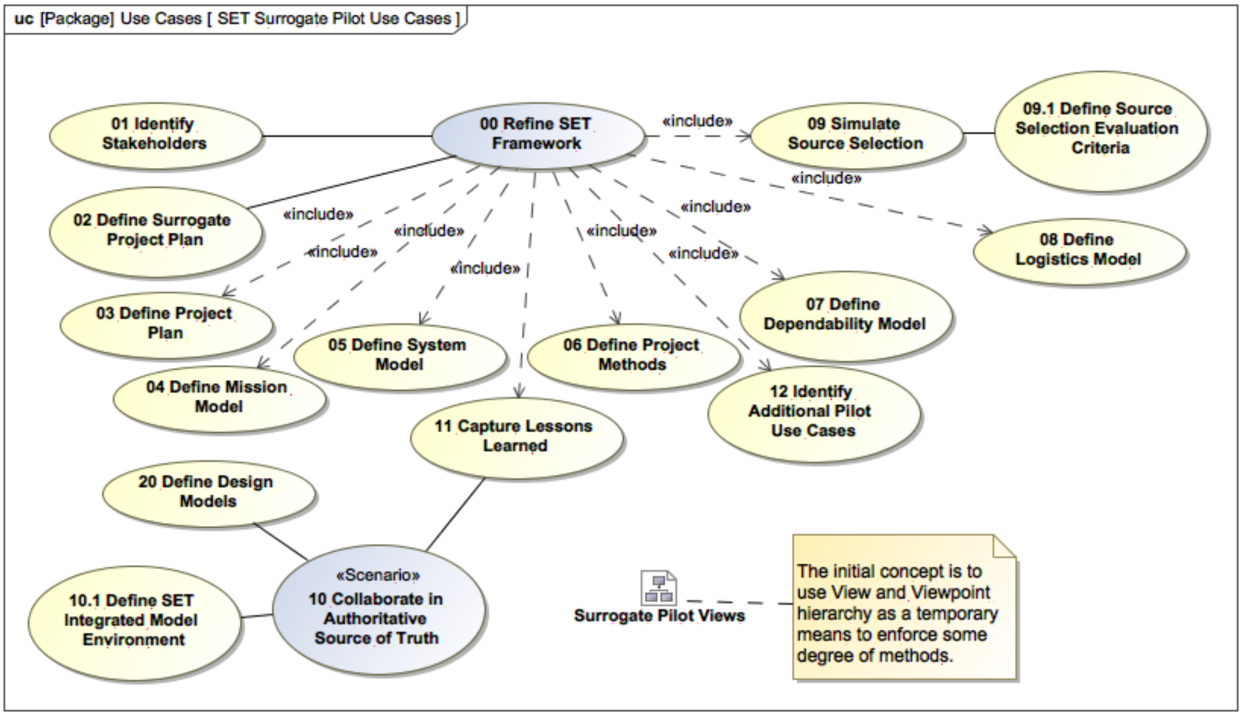
The new operational paradigm starts with mission engineering, analysis and acquisition led by government (Elements 1 & 2), and a collaborative design effort led by industry (Elements 3 & 4). Briefly the concept of the new SET framework for transforming from a document-centric process with monolithic reviews to an event-driven model-centric approach involves, but is not limited to:

- A concept for collaborative involvement between Government and Industry to assess mission and System of Systems (SoS) capability analyses, where NAVAIR has the lead
- Involve industry in SoS capabilities assessments during mission-level analysis (to the degree possible)
- Iteratively perform tradespace analyses of the mission capabilities using approaches such as Multidisciplinary Design, Analysis and Optimization (MDAO) as a means to develop and verify a model-based specification
- Synthesize an engineering concept system model characterized as a model-centric specification and associated contractual mechanism based on models or associated formalism
- At the contractual boundaries, industry will lead a process to satisfy the conceptual model addressing the Key Performance Parameters (KPPs), with particular focus on Performance, Availability, Affordability, and Airworthiness to create an Initial Balanced Design
- Industry too applies MDAO at the system and subsystem level
- There is a potential need to iterate back to re-balance the needs if the tradespace analyses of the solution/system for the program of record (POR) cannot achieve mission-level objectives
- All requirements are tradeable if they don't add value to the mission-level KPPs

- There are asynchronous activities in creating an Initial Balanced Design Government and Industry must work together to assess "digital evidence" and "production feasibility"

3.2.1 USE CASES

Figure 1.2. SET Surrogate Pilot Use Cases



Notionally, these are the primary use cases that are further defined within this surrogate project plan using a method based on the NASA/JPL Integrated Model Centric Engineering (IMCE) ontologies.

Table 1.1. Use Cases

Model Element	Documentation
00 Refine SET Framework	The main use cases is to Refine the SET Framework using a pilot project for simulating experiments while Executing the SET Framework.
01 Identify Stakeholders	Defined in following sections.
02 Define Surrogate Project Plan	This is what is reflected in this model. It is the plan about how to do Surrogate Experiments for assessing and refining the SET Framework. This document is produced from the model for the SET Surrogate Pilot.
03 Define Project Plan	This is the project plan for the surrogate system, currently referred to as Skyzer.
04 Define Mission Model	The Mission scenarios defined in Skyzer IM20.
05 Define System Model	The System model defined in Skyzer IM30.

Model Element	Documentation
06 Define Project Methods	The project methods covering various processes. This is the Skyzer project plan. There is a need to identify a stakeholder that can operate as the lead of the project.
07 Define Dependability Model	This use case is for modeling dependability, which include reliability, safety, etc., and would use modeling techniques based on Hazard Analysis and Failure Modes and Effects Analysis. A stakeholder needs to be identified to support this use case.
08 Define Logistics Model	This is a logistics model. We need to identify stakeholder(s) that can support this use case.
09 Simulate Source Selection	The use case is about simulating the source selection.
09.1 Define Source Selection Evaluation Criteria	This is the source selection evaluation criteria. This will likely evolve through additional pilot use cases.
10 Collaborate in Authoritative Source of Truth	This is the process by which we create and collaborate in the Authoritative Source of Truth (AST). This will involve the surrogate contractor(s) to "integrate" their environments with the NAVAIR surrogate pilot project IME.
10.1 Define SET Integrated Model Environment	This is the Integrated Model Environment (IME) that will be created by the NAVAIR surrogate pilot team, which is based on system modeling tools and OpenMBEE, the open source environment from NASA/JPL.
11 Capture Lessons Learned	This is a general set of lessons learned that we plan to capture from various internal and external stakeholder (e.g., other government organization and industry). This use case may include a more formal request for evaluating the surrogate pilot by directly examining the progress captured in the Authoritative Source of Truth (AST).
12 Identify Additional Pilot Use Cases	Define addition pilot use cases as we proceed through the execution of the first phase of use cases. Other examples include: mission systems, legacy system, Capability-Based Test and Evaluation, etc.
20 Define Design Models	This is the design created by the Surrogate Contractor. There will be many objectives placed on this use case that need to be assessed as part of a new operational paradigm between Government and Industry.

3.2.2 SURROGATE PROJECT MODELING APPROACH

There are several methods used to develop the NAVAIR surrogate pilot models (project, mission, system), and while there are a few traditional system model (SysML) views included in this model, this SET Framework Surrogate Pilot Project model uses the NASA/JPL IMCE ontologies as part of the Systems Engineering Research Center (SERC) research for this project. The figure shows a Partial Map of Foundation Ontology Concepts presented in a Module produced by NASA/JPL's Steve Jenkins. More information can be found here: https://nescacademy.nasa.gov/category/3/sub/17

Some example ontology definitions are included at the beginning of several section to illustrate how the ontology classes provide a basis for creating legal statements (as models) to characterize this project model. For example:

For clarification purposes these definitions were extracted from the NASA/JPL IMCE ontology. The ontologies have been transformed into profiles. Stereotypes from these profiles are used to allow the creation of legal sentences (axioms) about stakeholders, concerns, missions, objectives, projects, requirements, and components that comply with the ontologies. A few examples are provided here.

A `Stakeholder` is a person or organization with a recognized interest in the successful completion of a `Project` or `Program`. Example `Stakeholders` include: executives, subject matter experts, engineers, and industry contractors.

A `Person` corresponds to an individual named person. A `Person` belongsTo zero or more `Organizations`.

A `Role` corresponds to a set of assignments meant to be filled by a single `Person`.

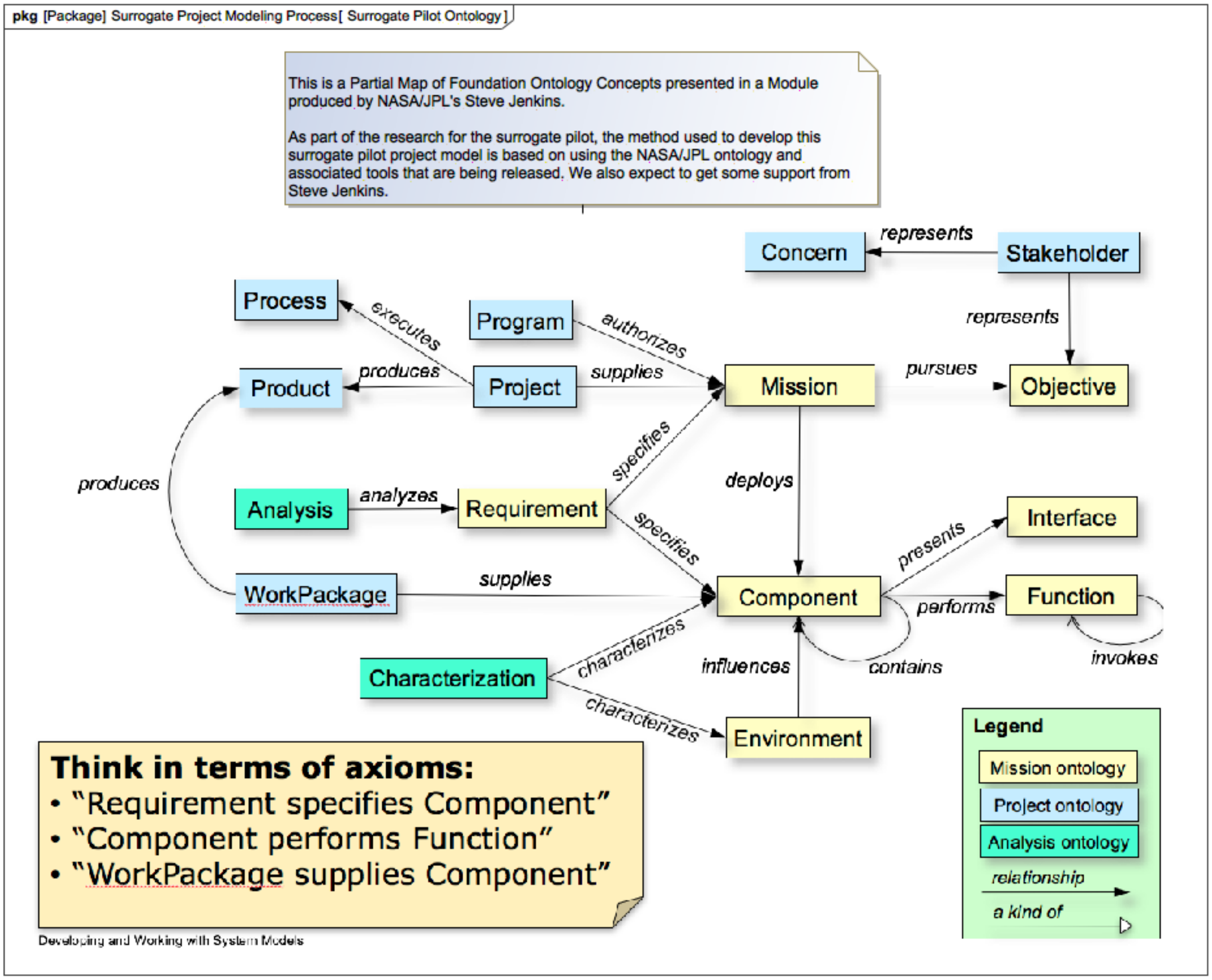
A `Mission` is a `PerformingElement` that pursues `Objectives`.

A `Mission` may contain `Components`, but the preferred relationship is that a `Mission` deploys its systems (which are `Components`). This convention allows for a `Mission` to be associated with shared or external `Components` that it does not strictly contain.

An `Objective` represents a specific interest that one or more stakeholders have in the successful execution of a mission. Example `Objectives` include charactering how to Execute the SET Framework.

`Objectives` differ from `Requirements` in that they are not the result of negotiated agreement between customer and supplier, they need not be mutually consistent, and a `Mission` pursues but need not completely achieve all its `Objectives`. In a sense, the set of `Requirements` for a `Mission` represents the minimum acceptable achievement of `Objectives` for a given cost, schedule, and risk.

Figure 1.3. Surrogate Project Modeling Approach



As part of the research for the surrogate pilot, the method used to develop this surrogate pilot project model is based on using the NASA/JPL ontology and associated tools that are being released. We also expect to get some support from NASA/JPL's Steve Jenkins.

3.3 CHAPTER 2. SURROGATE PILOT CONTEXT

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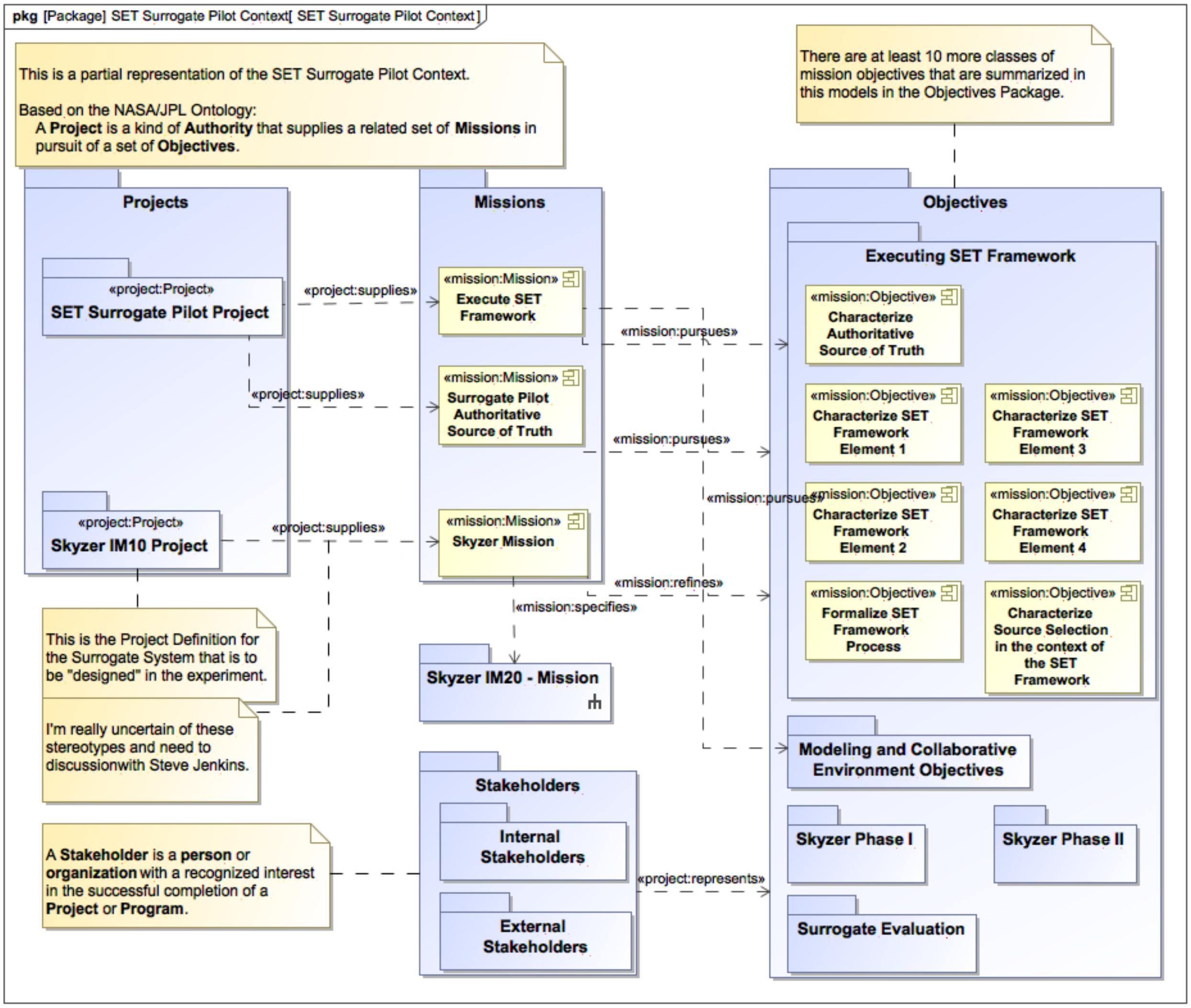
3.3.1 SET Surrogate Pilot Context

As discussed in Chapter 1, this project plan is modeled to comply with the NASA/JPL IMCE ontologies. A `Project` is a kind of `Authority` that supplies a related set of `Missions` in pursuit of a set of `Objectives`. `Stakeholders` represent `Objectives`.

Figure 2.1. SET Surrogate Pilot Context



3.3.2 Stakeholders

This is an initial list of stakeholders. Specific individuals are identified when possible, otherwise organizations that need to provide stakeholders are identified.

3.3.2.1 External Stakeholders

Table 2.1. External Stakeholders

Model Element	Documentation
Government	Government individuals that may participating in observing and commenting on the surrogate pilot.
Industry Contractor	Industry contractors that may participate in reviewing the surrogate pilot.
NASA JPL	This includes individuals that may contribute such as Chris Delp the lead on OpenMBEE and reviewers from NASA/JPL such as Chi Lin and Steve Jenkins.
SERC Sponsor	
ST4SE	This is the Semantic Technologies four Systems Engineering (ST4SE) team, which includes Mark Blackburn, Mary Bone, Steve Jenkins from NASA/JPL, Barry Smith, Chris Paredis, Henson Graves, etc. may be able to help apply ontologies to this program.

3.3.2.2 Internal Stakeholders

At the request of the NAVAIR sponsor, the list and roles of the internal stakeholders has been removed.

3.3.2.3 Surrogate Contractor Stakeholders

At the request of the NAVAIR sponsor, the list and roles of the surrogate contractor stakeholders has been removed.

3.3.3 CONCERNS

A `Concern` represents a specific interest that one or more `Stakeholders` have in the successful completion of a `Project` or `Program` and its `Missions`.

A `Mission` is a `PerformingElement` that pursues `Objectives`.

An `Objective` represents a specific interest that one or more stakeholders have in the successful execution of a mission. Example `Objectives` include charactering how to Execute the SET Framework.

For this reason, and because we are formalizing objectives in this model, many of the concerns have been formalized as more specific objectives that need to be characterized throughout this effort

Objectives are elaborated in the following chapter.

3.3.3.1 Assess and Refine SET Framework

Table 2.4. Assess and Refine SET Framework

Model Element	Documentation
Must right size the Capability Description Document	Some examples characterized by Dave Cohen: 1. Narrow top of the requirements pyramid

Model Element	Documentation
	2. Off-load requirments to other elements of SoS and via TTPs (CONOPS) 3. KPPs must be tied to mission effectiveness, Ao or Cost
The Systems Engineering Technical Reviews events takes too long	The traditional process for performing Systems Engineering Technical Review (SETR) events takes too long, happens too late, and does not take advantage of capabilities that would permit more continuous and asynchronous events.
Time to develop capabilities is too long	The time it takes to get new capabilities into the field is not keeping pace with the changing threats.

3.3.3.2 Modeling and Collaboration Environment Concerns

Table 2.5. Modeling and Collaboration Environment Concerns

Model Element	Documentation
Ability to ensure Enterprise Governance to Modeling Environment	
Ability to share with stakeholders	
Ability to work and collaborate in an unclassified environment	
Ability to work and collaborate in classified environment	

3.4 Chapter 3. Surrogate Pilot Objectives

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This section starts from the Mission perspective of the SET Framework Execution. This section is evolving and presents a non-exhaustive set of mission objectives for Executing the SET Framework. These objectives will be defined and related, and there will be traceability created to show how the objectives are satisfied during the execution of the SET framework through the development of the Mission, System, and Design models.

The model representations used in this section are based on the NASA/JPL Mission ontology, which defines concepts for describing missions in terms of:

- Objectives (this section)
- Constituent components
- Functions those components perform
- Requirements that specify them

The objectives are organized into about 10 classes that are presented in subsections of the chapter. Each subsection has one or more models (diagram) of the objectives that associate key stakeholder(s) with one or more objectives. These models formalize information and relationships that have been evolving in Power Point briefings. At the end of each section is a table that provides more information about each objective.

Objectives differ from Requirements:

- They are not the result of negotiated agreement between customer and supplier
- They need not be mutually consistent
- A Mission pursues but need not completely achieve all its Objectives

3.5 EXECUTING SET FRAMEWORK OBJECTIVES

Figure 3.1. Executing SET Framework

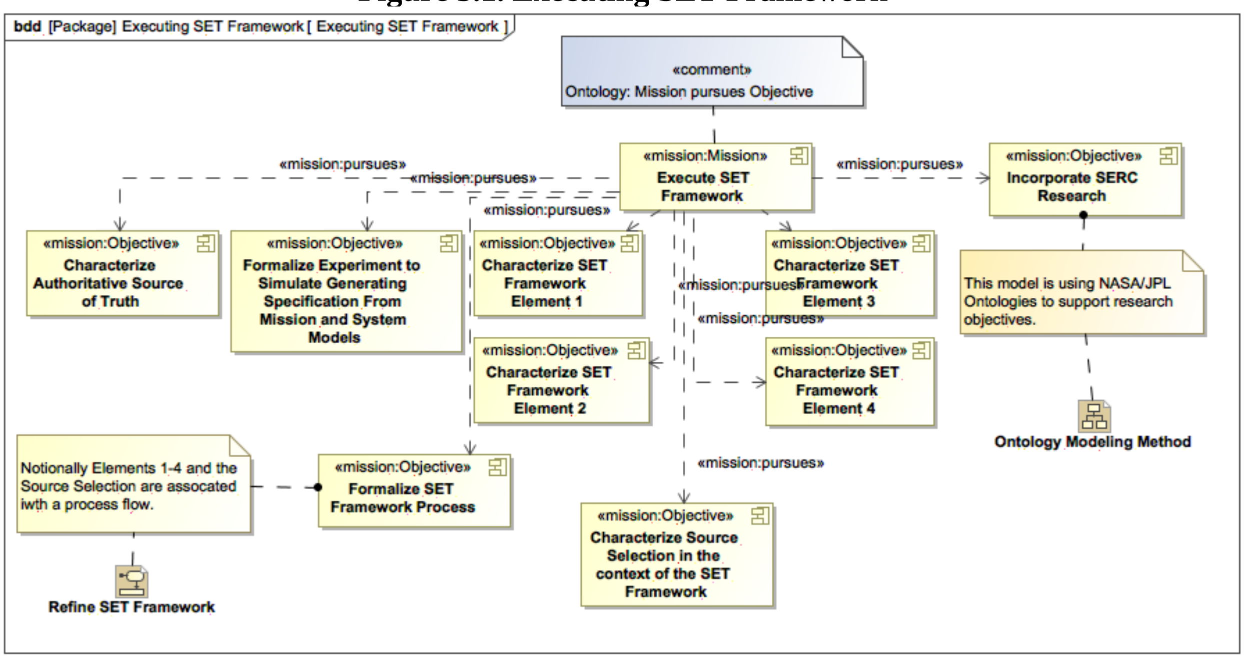
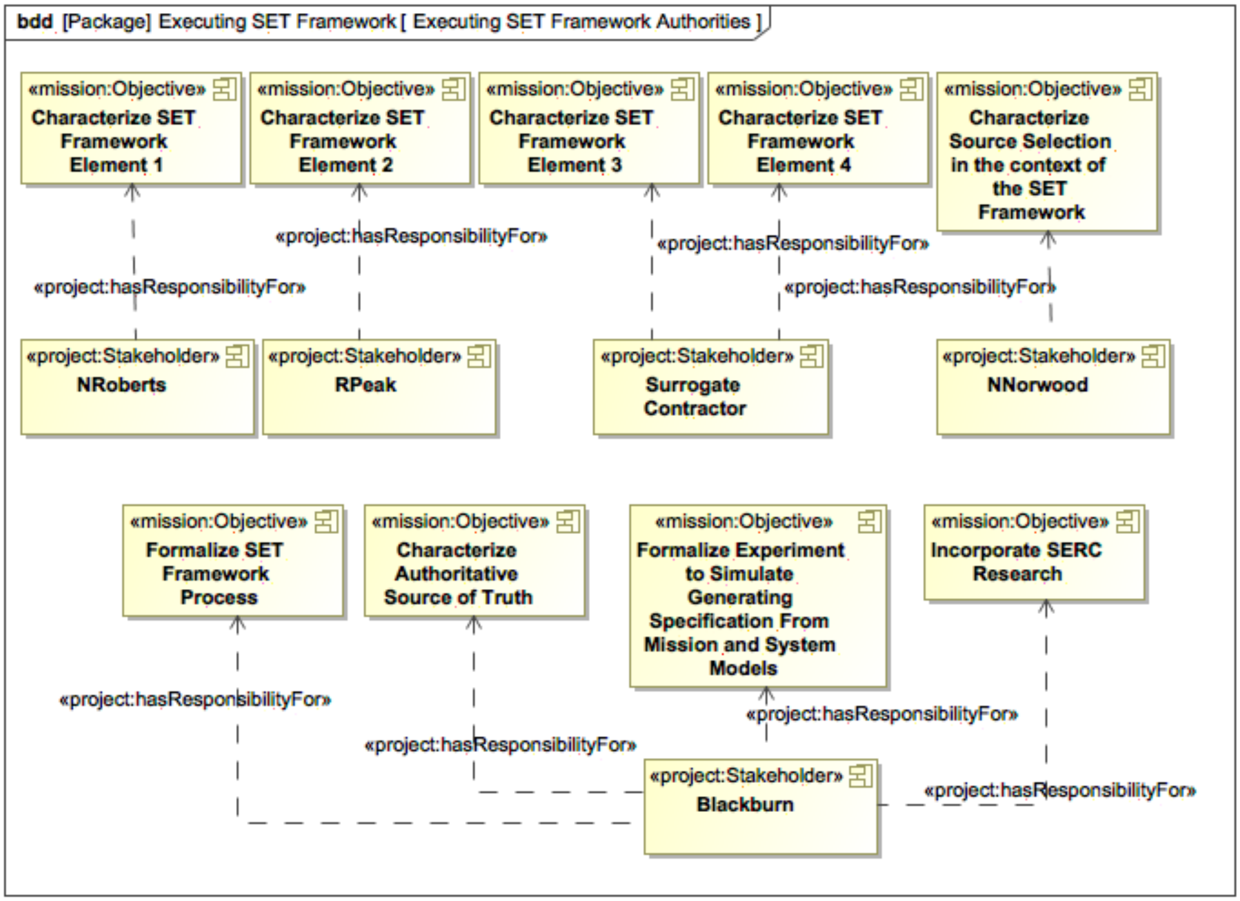


Figure 3.2. Executing SET Framework Authorities



This view uses the <<project:hasResponsibilityFor>> relation to show those project stakeholders that have the primary responsibility for mission objectives.

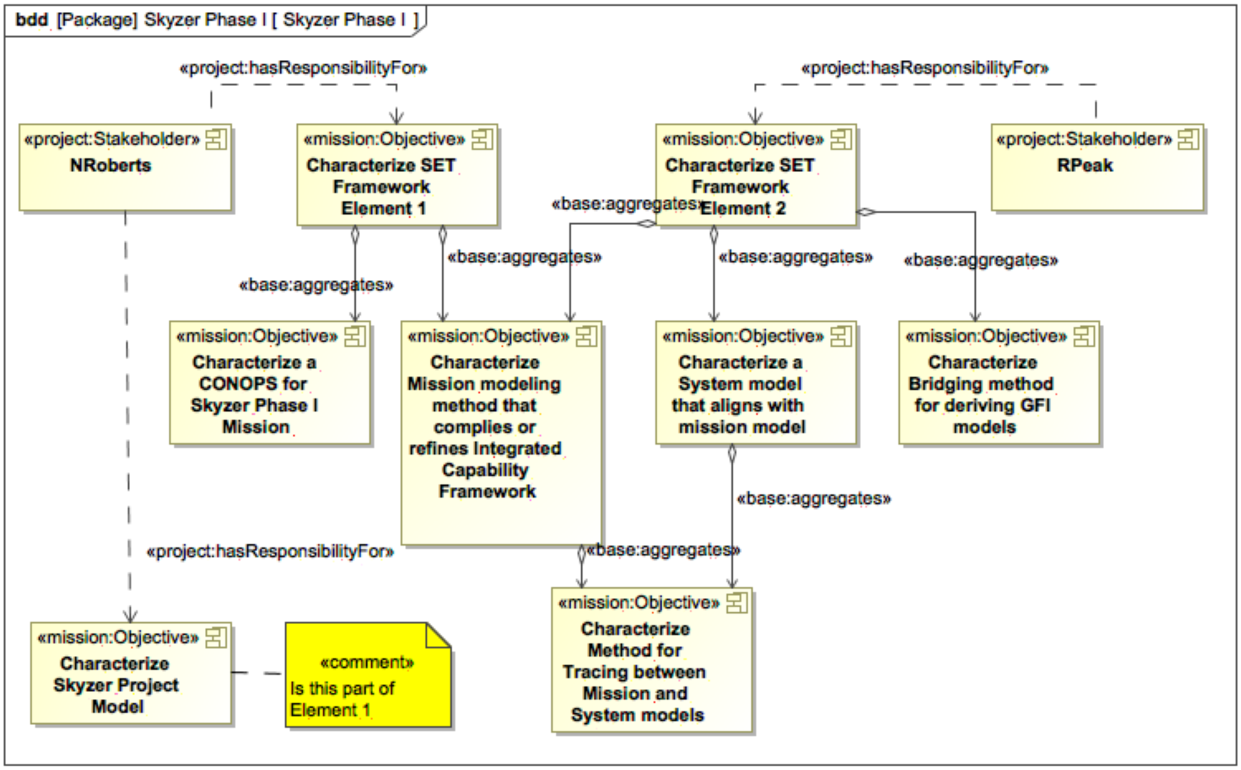
Table 3.1. Executing SET Framework Objectives

Model Element	Documentation
Characterize Authoritative Source of Truth	Develop a prototype infrastructure that can be used by both Government/SERC team to support Element 1 & 2, and that can also be "integrated" while conducting Insight/Oversight for collaboration with Surrogate contractors in Element 3 & 4.
Characterize SET Framework Element 1	Element 1 is fundamentally about mission modeling, but has other aspects. For example, does it include how the Integrated Warfare Analysis establishes CONEMPS and Effects-Chains and how they are modeled at the System of Systems (SoS) level? Therefore the objective is about characterizing all facets associated with Element 1.
Characterize SET Framework Element 2	Element 2 is also fundamentally about developing a System Model, synthesizing a specification, but it also factors in aligning the system model with the mission model and Key Performance Parameters.
Characterize SET Framework Element 3	Element 3 starts when the contract has been awarded. Element 3 is where the contractor refines the design awarded under contract. The key aspects for the

Model Element	Documentation
	pilot is to understand how subject matter experts from NAVAIR are able to view, measure maturing designs in a collaborative environment (the AST). In addition, the pilot seeks to assess new operational approaches to contract modifications that are performed directly in models.
Characterize SET Framework Element 4	It is unclear what happens in Element 4.
Characterize Source Selection in the context of the SET Framework	The objective is to perform source selection in the context of models. The objective is to have the Government Furnish Information (models) that are provided as part of the RFP, be elaborated, corrected and refined by the surrogate contractors. We need to characterize exactly when this happens between Element 2 and Element 3 and all of the rules that govern Industry and Government collaboration.
Formalize Experiment to Simulate Generating Specification From Mission and System Models	This section of the model is characterizing many of the objectives that need to be formalized as experiments, for determining how mission and system models are used to generate a "specification" directly from models. The objective should potentially go beyond what might actually be needed in terms of modeling to demonstrate "how" rigorous and comprehensive modeling can be done. The experiments must also "seed" defects in the RFP delivered models to allow for understanding potential change management approaches in model-based acquisition under the SET Framework.
Formalize SET Framework Process	While it may not actually be necessary or possible to fully characterize the SET Framework Process, there are research merits to illustrate the concept of a process model, especially specific types of feedback loops that are related to operational interactions between the Government and the Surrogate contractor.
Incorporate SERC Research	The key research topics are: cross-domain model integration, model integrity, modeling methods, ontologies and many derived topics such as working collaboratively an authoritative source of truth (AST), which leads into the Integrated Modeling Environment (IME). A key reason for creating this type of model for the SET Surrogate Pilot project is to satisfy research requirements characterized in the SERC research task for the SERC collaborators.

3.6 SKYZER PHASE I OBJECTIVES

Figure 3.3. Skyzer Phase I



This model illustrates the <<base:aggregates>> relation from the IMCE ontologies, which provides a means to relate objectives.

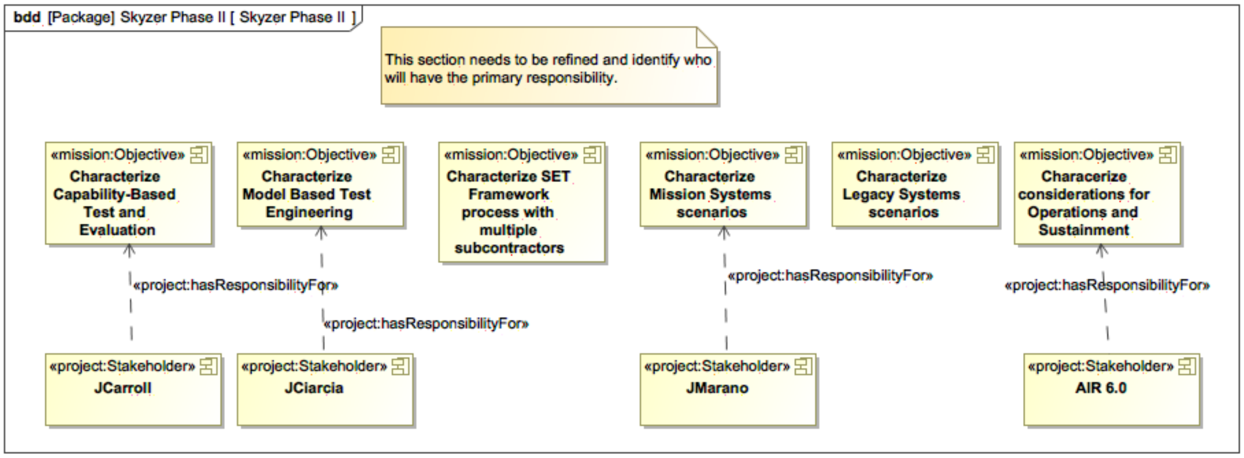
Table 3.2. Skyzer Phase I Objectives

Model Element	Documentation
Characterize a CONOPS for Skyzer Phase I Mission	This should define the CONOPS that will be refined by the Mission Model.
Characterize a System model that aligns with mission model	This is the system model that will be used with Bridging method/mechanism to produce both the generated specification as well as the Government Furnished Information (GFI) that will be part of the Request for Proposal (RFP) and used in source selection.
Characterize Bridging method for deriving GFI models	This is a concept for taking analysis derived modeling and bridging the specific information that is needed to go into a Government Furnished Information (GFI) model for purpose of Request for Information (RFI), Request for Proposal (RFP) and/or source selection.
Characterize Mission modeling method that complies or refines Integrated Capability Framework	The current approach for performing mission area analysis is based on the Integrated Capability Framework. This objective should demonstrate how model support or subsumes these guidelines.

Model Element	Documentation
Characterize Skyzer Project Model	The objective is to define the Skyzer Project modeling guidelines, which currently includes the characterization of mission and system modeling methods. Does this occur in Element 1?

3.7 SKYZER PHASE II OBJECTIVES

Figure 3.4. Skyzer Phase II



Scott is lead for the SET Framework Links.

Table 3.3. Skyzer Phase II Objectives

Model Element	Documentation
Characerize considerations for Operations and Sustainment	Determine what type of information should be captured during the early stages of SET Element 1 and 2 phases that will better help with Operations and Sustainment.
Characterize Capability-Based Test and Evaluation	This is the concept discussed by Jim Carroll. The objective is to bring this capability in early and understand the implications on process. This may have impacts on source selection criteria.
Characterize Legacy Systems scenarios	This objective looks to evaluate and characterize how the SET Framework should be used for legacy systems. This particular question came from industry during briefings on the surrogate pilot.
Characterize Mission Systems scenarios	There is a belief that most ongoing changes and future changes will involve mission systems, and Phase II of the surrogate pilot should be structure like a block upgrade, which provides an opportunity to provide scenarios for involving Mission Systems for the flight vehicle.
Characterize Model Based Test Engineering	This should bring in the capabilities of the Model Based Test Engineering research performed by Jim Ciarcia. This includes metamodels that represent and ontology for many phases of this process. The addition objectives are to bring these concepts in early.

Model Element	Documentation
Characterize SET Framework process with multiple subcontractors	

3.8 Modeling Methods Objectives

Figure 3.5. Modeling Methods

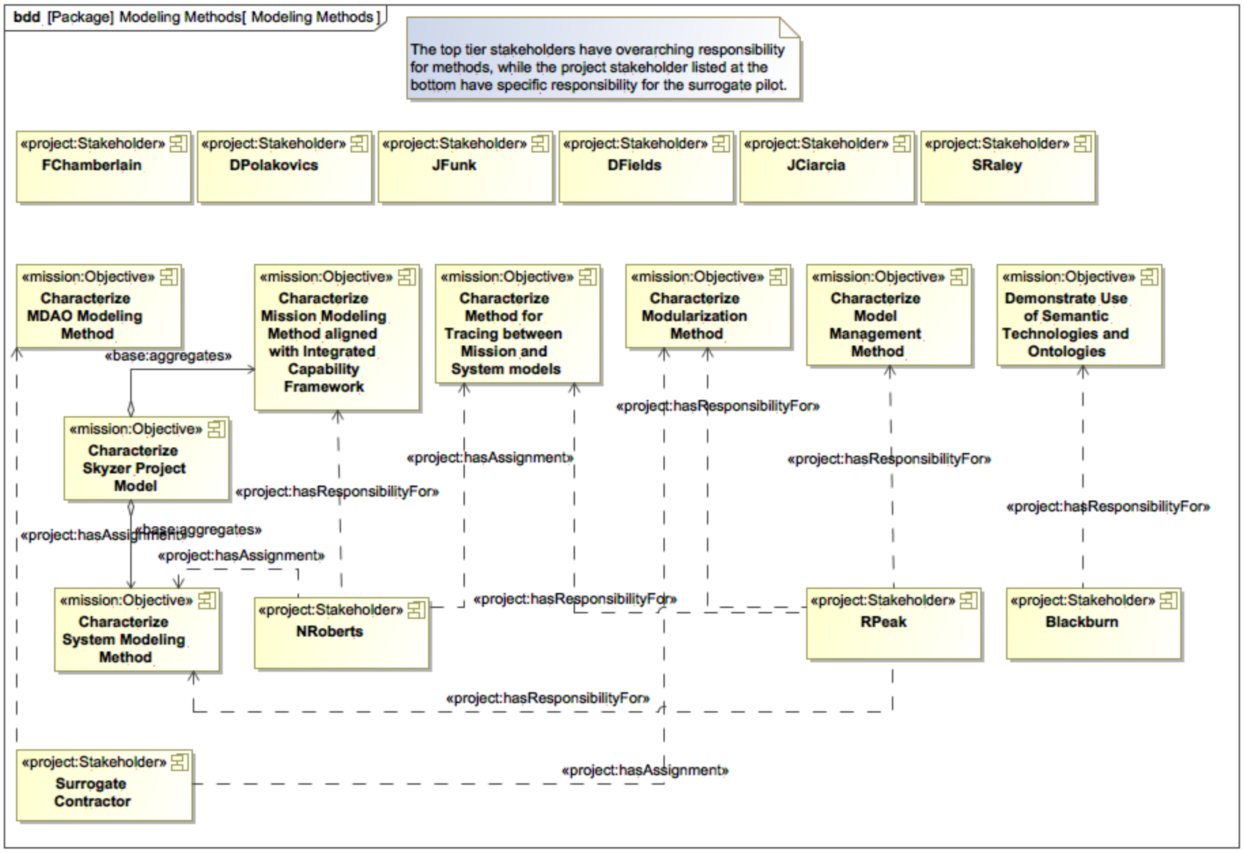


Table 3.4. Modeling Methods Objectives

Model Element	Documentation
Characterize MDAO Modeling Method	The method for Multidisciplinary Design, Analysis and Optimization (MDAO) has been demonstrated in the SERC RT-168 research for CONOPS and system-level modeling. This objective seeks to characterize this through the use of examples and demonstrations for the surrogate pilot, and will carry this out using Phoenix Integration ModelCenter for the SERC researchers, but the Surrogate Contractor has their own MDAO tools.
Characterize Method for Tracing between Mission and System models	Need to characterize how the surrogate contractor can extend the system model and trace to discipline/domain-specific models, which also traces back up to the mission model. Should this also trace to CONOPS or CONEMPS? In the context of the model management method, where should the

Model Element	Documentation
	traceability linkages be created?
Characterize Mission Modeling Method aligned with Integrated Capability Framework	The objective is to defined a mission modeling method that aligns with the Integrated Capability Framework. This characterizes the processes for Mission Technical Baseline and the Integrated Capability Technical Baseline.
Characterize Model Management Method	The objective is to define one or more model management methods that can support a new operational paradigm specifically focused on new approaches to contracting that can operation more like software change control.
Characterize Modularization Method	
Characterize System Modeling Method	This characterizes the system modeling method. The initial recommendation was to use OOSEM, but can this apply to all type of programs?
Demonstrate Use of Semantic Technologies and Ontologies	There are many objectives for using Semantic Technologies and ontologies for formalizing methods and to support cross-domain model integration through interoperability of ontologies data. In addition, this particular model element is based on the NASA/JPL IMCE ontologies.

3.9 REAL-TIME COLLABORATE IN AST OBJECTIVES

Figure 3.6. Real-time Collaboration in AST

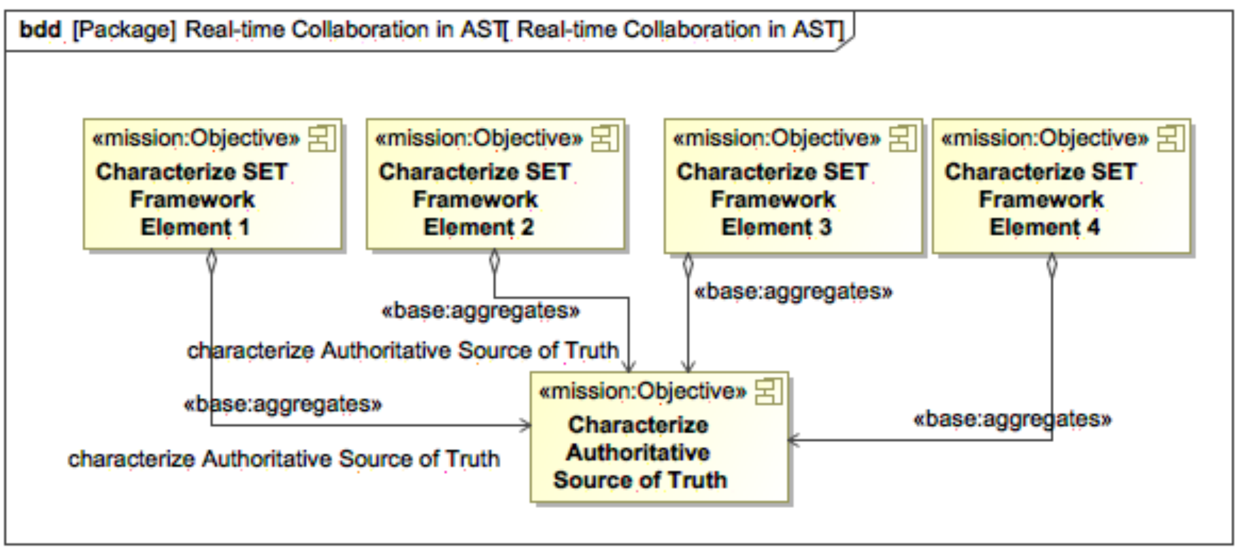


Figure 3.7. Use Cases for Collaboration Environment and Authoritative Source of Truth

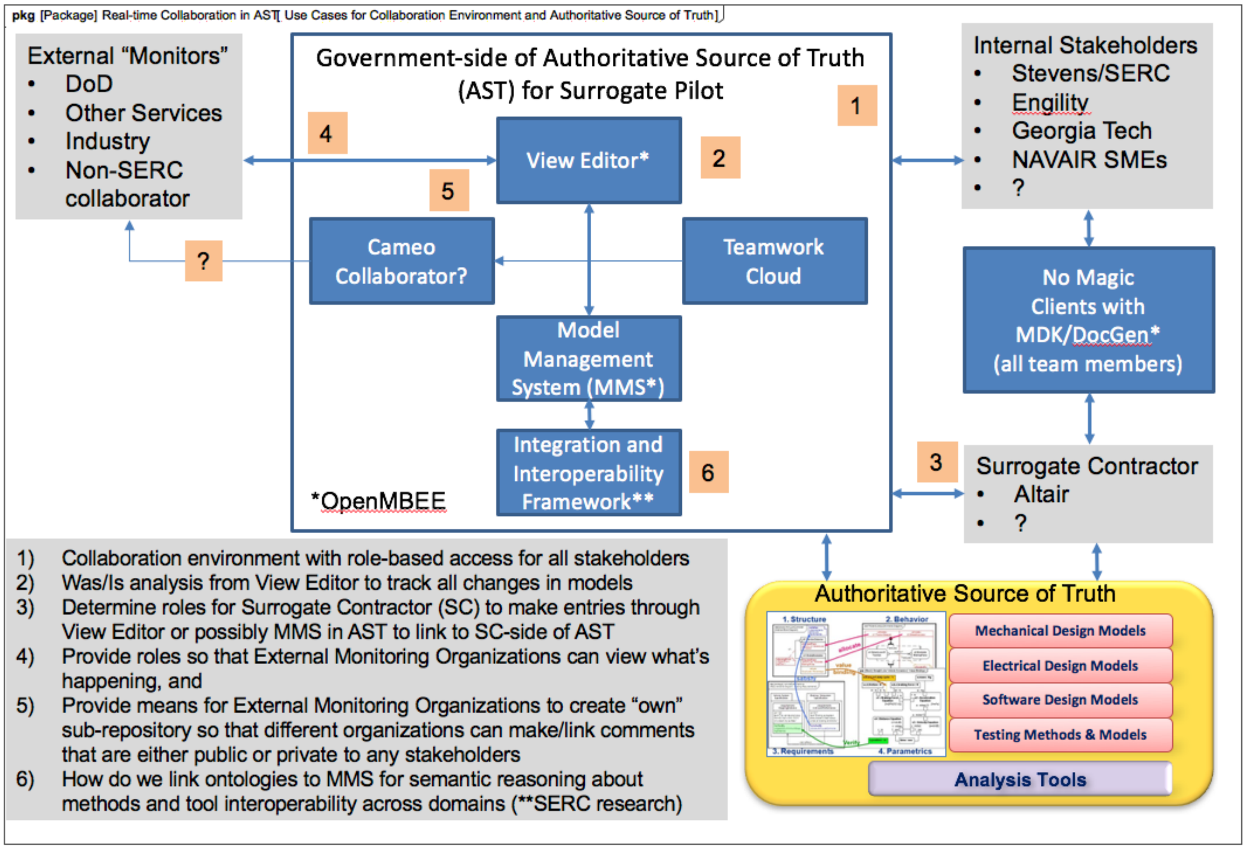


Table 3.5. Real-time Collaborate in AST Objectives

Model Element	**Documentation**
Characterize Approach for Integrating Government and Industry Environments in AST	This will include, but not be limited to: 1. Collaboration environment with role-based access for all stakeholders 2. Was/Is analysis from View Editor to track all changes in models 3. Determine roles for Surrogate Contractor (SC) to make entries through View Editor or possibly MMS in AST to link to SC-side of AST 4. Provide roles so that External Monitoring Organizations can view what's happening, and 5. Provide means for External Monitoring Organizations to create "own" sub-repository so that different organizations can make/link comments that are either public or private to any stakeholders 6. How do we link ontologies to MMS for semantic reasoning about methods and tool interoperability across domains (**SERC research)
Characterize Process for Insight and Oversight in AST	

Model Element	Documentation
Package Modeling Environment as part of Collaboration	The concept is to use Docker in order to allow the development environment used to produce the Initial System Model to be shared with the Surrogate Contractor.
Set up Collaborative Environment for AST	
Use of OpenMBEE MMS to Demonstrate Model Management	A key driver for NASA/JPL developing OpenMBEE was to provide model management at a fine level of granularity and be completely tool agnostic. This should provide a means for providing details tracking of changes that can support a new operational paradigm for managing contracts.

3.10 DECISION FRAMEWORK OBJECTIVES

Figure 3.8. Decision Framework

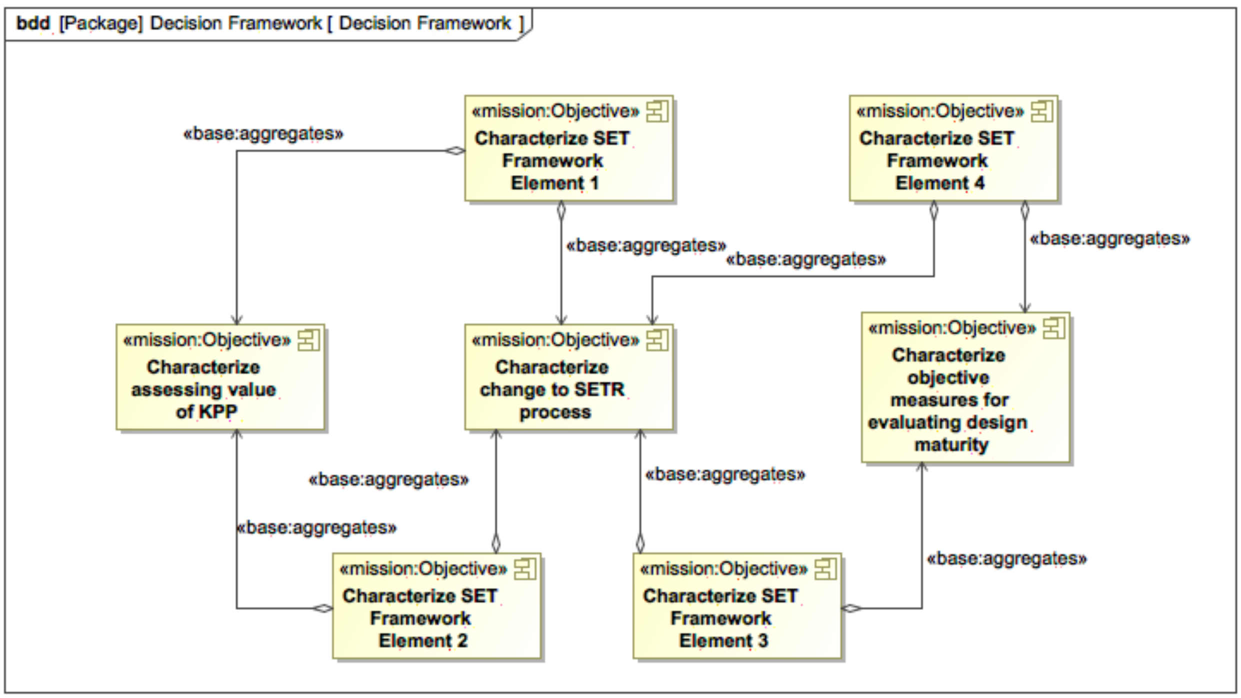


Table 3.6. Decision Framework Objectives

Model Element	Documentation
Characterize assessing value of KPP	A possible Decision Framework research tool and method for assigning value to KPPs is being applied to different case studies on the ARDEC research task RT-168.
Characterize change to SETR process	This objectives investigate how the SETR process/guidebook/checklist can be refined or modified by being able to make assessments more objectively within models. There is research that has started an ontology from the SETR guidebook. Can this be part of the objectives measures?
Characterize objective	This is a new process to allow for continuous asynchronous decision making

Model Element	Documentation
measures for evaluating design maturity	about a maturing design as opposed to the traditional monolithic events (e.g., SRR, PDR, CDR). It is unclear if the objective measure apply to Element 1 or 2.

3.11 Source Selection Objectives

Figure 3.9. Source Selection

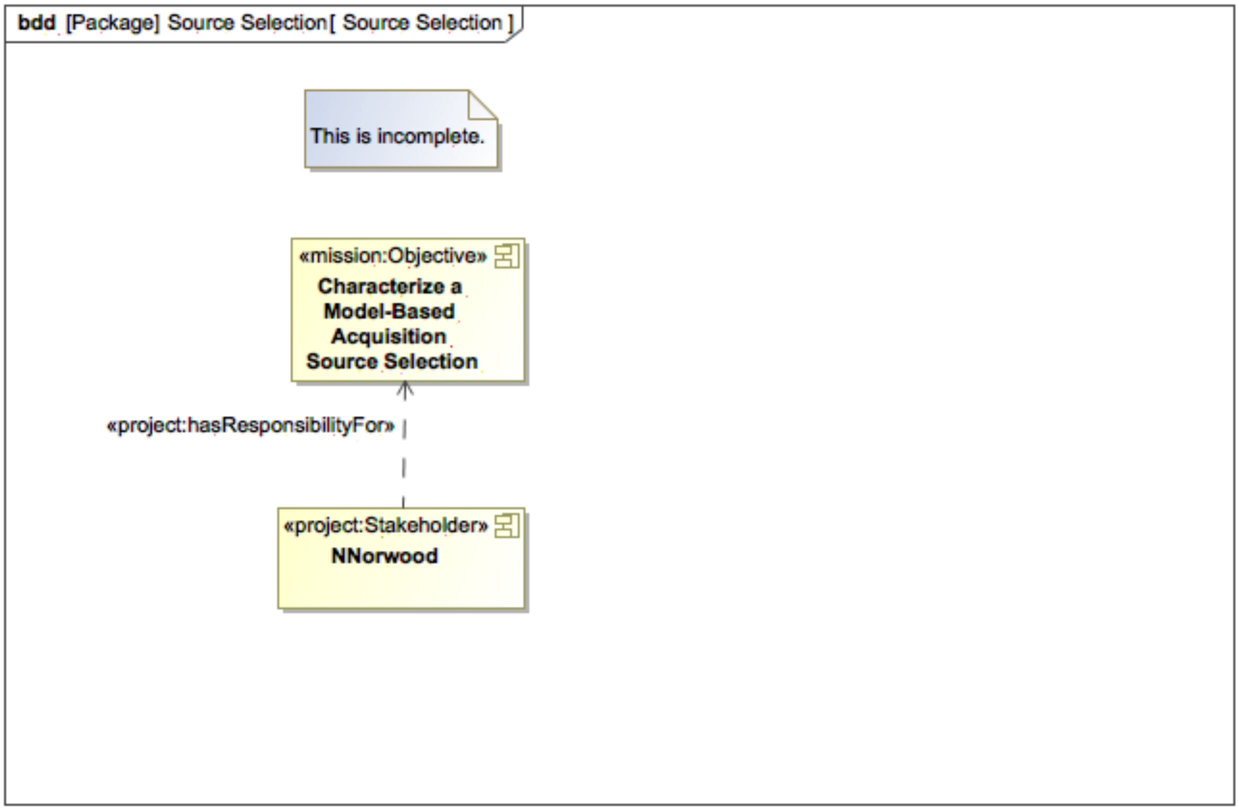


Table 3.7. Source Selection Objectives

Model Element	Documentation
Characterize a Model-Based Acquisition Source Selection	

3.12 Operations and Policy of Contracting Objectives

Figure 3.10. Operations and Policy of Contracting

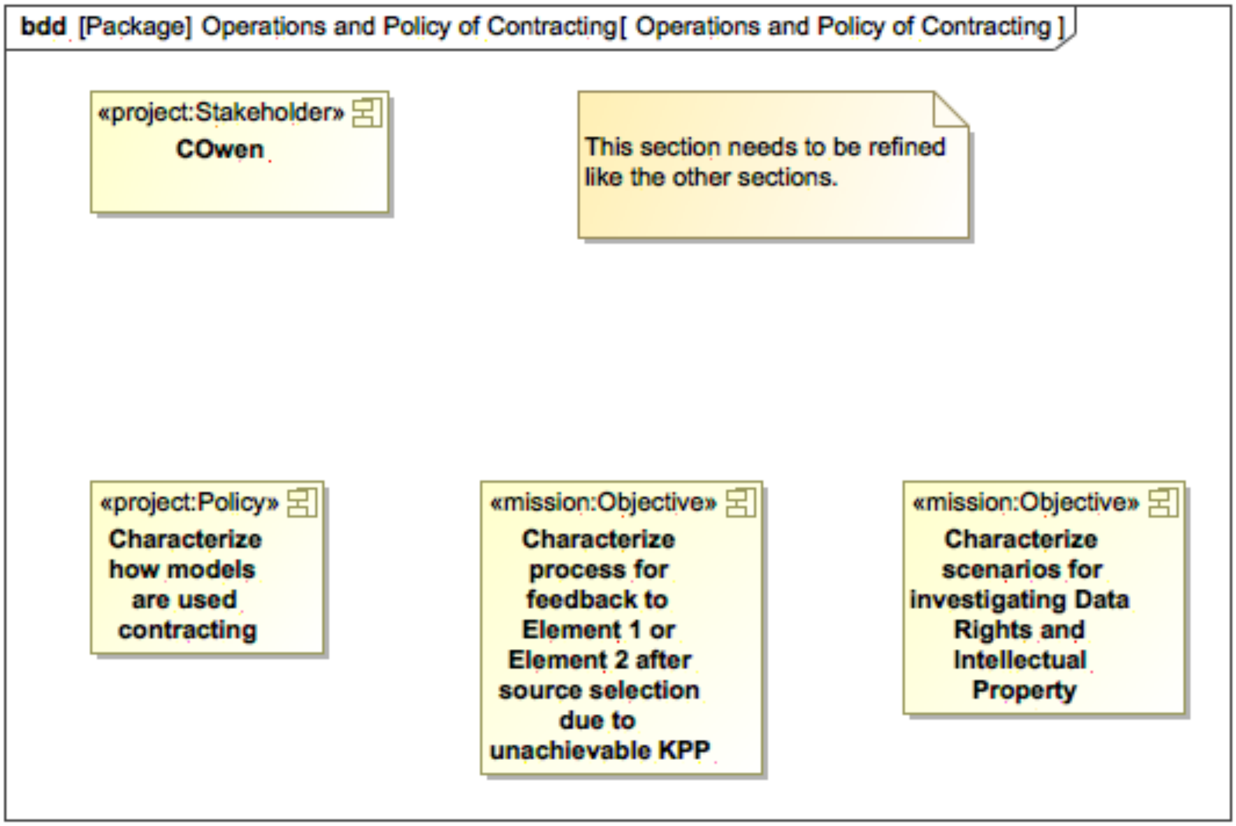


Table 3.8. Operations and Policy of Contracting Objectives

Model Element	**Documentation**
Characterize how models are used contracting	Investigate the potential
Characterize process for feedback to Element 1 or Element 2 after source selection due to unachievable KPP	The objective is to determine processes enabled by modeling and all association enabling technologies for contracting related feedback due to issues in the contract after source selection.
Characterize scenarios for investigating Data Rights and Intellectual Property	Consider looking at the document from the Aerospace Industry Association CONOPs. Who owns the different models? Recall the approach used by NAVSEA and Huntington Ingalls called the Product Data Model (PDM) that was presented at the 2016 Model Centric Engineering Government and Industry Day.

3.13 VISUALIZATION OBJECTIVES

Figure 3.11. Visualization

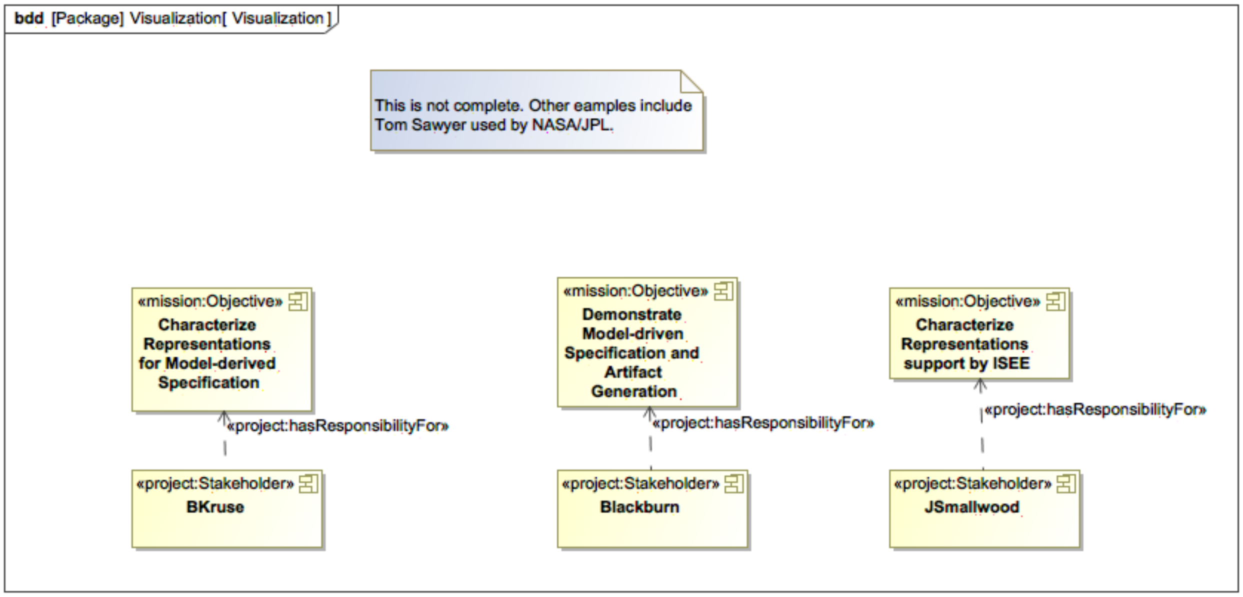


Table 3.9. Visualization Objectives

Model Element	Documentation
Characterize Representations for Model-derived Specification	
Characterize Representations support by ISEE	These are existing mechanisms that will support visualizations.
Demonstrate Model-driven Specification and Artifact Generation	The objective is to demonstrate the uses of model-driven specifications to support contracting as well as other artifacts to provide the appropriate view and viewpoints relevant to different stakeholders.

3.14 SURROGATE EVALUATION OBJECTIVES

Figure 3.12. Surrogate Evaluation

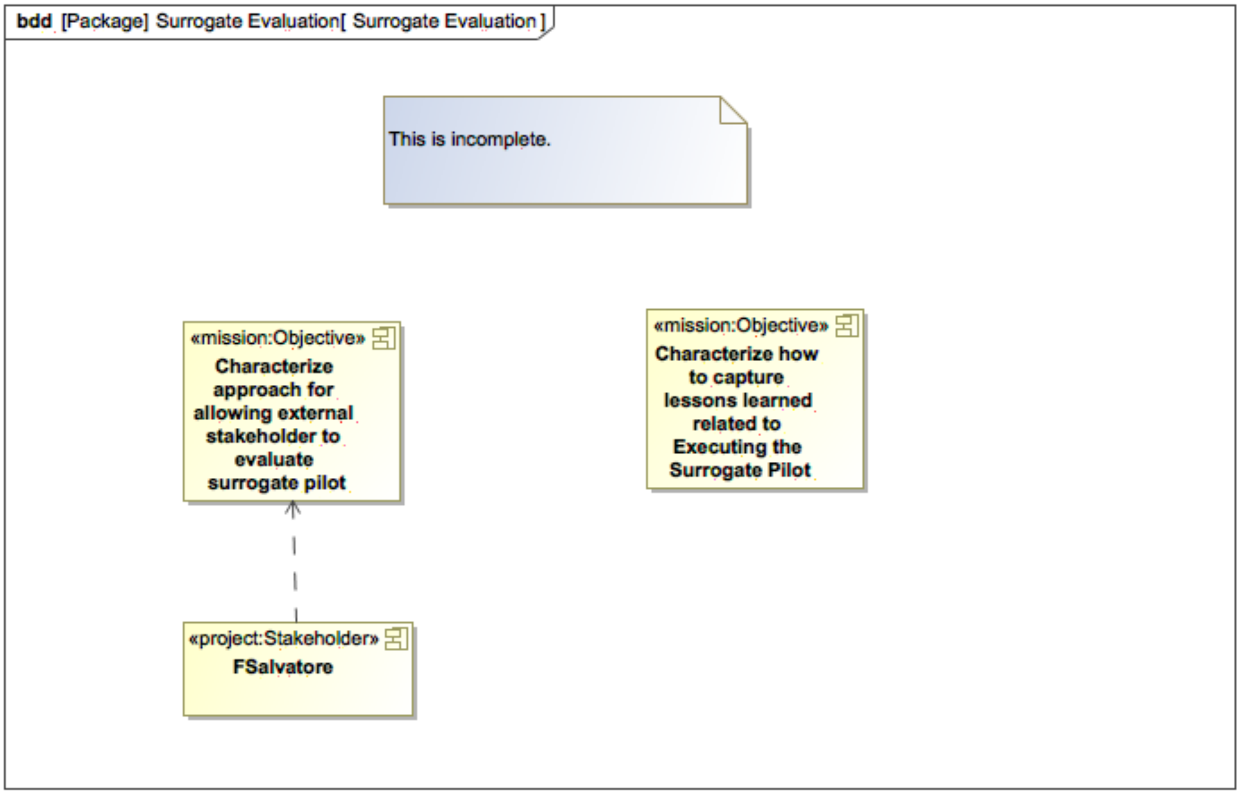


Table 3.10. Surrogate Evaluation Objectives

Model Element	Documentation
Characterize approach for allowing external stakeholder to evaluate surrogate pilot	This needs to refine the idea that we can selectively allow external stakeholders permission to log in to the Authoritative Source of Truth repository and provide ongoing feedback to all facets of the approach used on various phases of surrogate pilot.
Characterize how to capture lessons learned related to Executing the Surrogate Pilot	We need to characterize how we are going to capture lessons learned during the execution of numerous phases of this pilot, including capturing (potentially) anonymously information from external stakeholders such as Industry and Govenment organizations other than NAVAIR.

4 UC00: ONTOLOGIES AND SEMANTIC WEB TECHNOLOGIES

This use case investigates the development and use of ontologies and more generally semantic web technologies (SWT) for reasoning about completeness and consistency across cross-domain models. These capabilities support enforcement of modeling methods and support for model integration through interoperability. We summarize some research findings and our efforts related to SWT in this section. For example, we have developed the Integration and Interoperability Framework (IoIF), which has been used for preliminary demonstration to support this concept. We plan to look into the use of our research on the surrogate pilot.

There is increased interest in the topic of ontologies and SWT as awareness has increased significantly in the past two years. We believe SWT may be enablers for an AST, tool-agnostic approaches to methodology enforcement, and conformance that also support model integrity as reflected in Figure 6. This section summarizes some of the relevant efforts over the past year on this topic in addition to the description and examples in Section 3 that explains how we are using the NASA/JPL IMCE ontologies [87] in the surrogate pilot. It is also important to say that SWT is an enabler for capabilities such as computational intelligence (e.g., Artificial Intelligence, etc.), because they provide a means for representing knowledge. We see these capabilities coming to use in both the systems we build and deploy, as well as in the systems engineering systems we use to analyze and development systems moving forward.

4.1 Challenge of Cross-Domain Model Integration

We believe that organizations should take advantage of tool-to-tool integration when possible, but in working with our sponsors and interacting with industry and government organizations, this is not always possible or it can be challenging. The challenge of cross-domain modeling integration can be illustrated using the following example. While an aircraft may have thousands of objects, consider the relationships for a refueling value of a UAV, as shown in Figure 10. There is one object discussed in this example (i.e., Valve), however, there are many domains that bring in cross-domain relationships to that Value, along with other objects, such as:

- Mechanical **Domain**
  - Valve connects to a Pipe
- Electrical **Domain**
  - Switch opens/closes Value
  - Maybe using a combinations of hardware and software
- Operator **Domain**
  - Pilot remotely sends message to control Value
- Communication **Domain**
  - Messages sent through networks: 1) within the aircraft system, and 2) from the remote operator
- Fire control **Domain**
  - Independent detection to shut off Valve
- Safety **Domain**
  - Looks top-down at potential hazards through Fault Tree Analysis (FTA)
  - Looks bottom-up using Failure Models and Effects Analysis (FMEA) to analyze failure impacts from specific designs of components

Figure 10. Example of Cross Domain Relationships Needed for System Trades, Analysis and Design

A problem is understanding the cross-domain impacts of designs and analyses that might be needed if one object within these related domains change. In general, there are different tools used in different domains, and the tools are often not integrated, nor are they able to share semantically-relevant data. Tool integrations are often dynamic consequences of customer requirements to continue improving the tools, thus the tools are constantly being updated, which further adds to the challenge of tool-to-tool integration. Tool integrations are not simply statically putting a certain set of tools together. Depending on the varying needs of tasks from particular stakeholders, the types of tools needed, their execution sequences, the interdependencies of data flow among them vary from case to case. In addition, the problem often gets worse when attempting to maintain an integration for different versions of tools. Figure 11 illustrates the dynamic nature of tool integration [144].

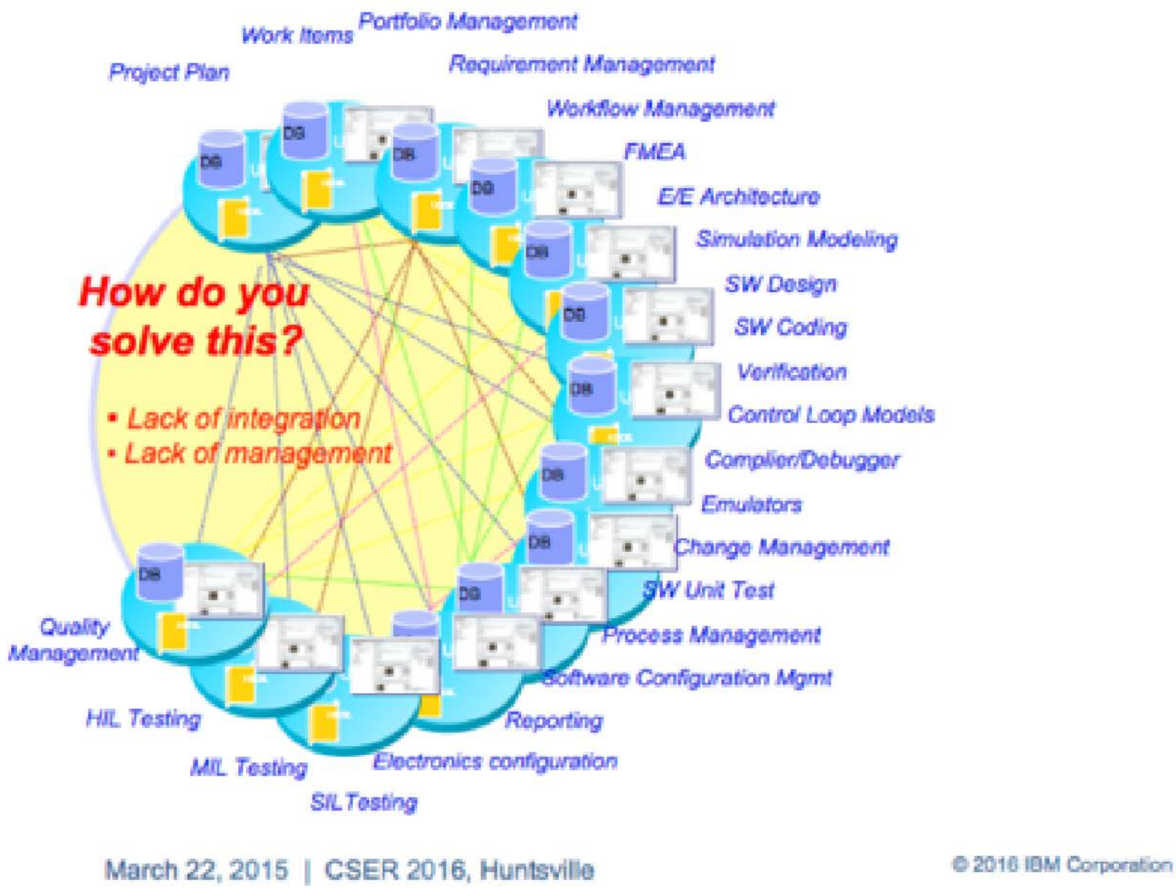


Figure 11. Coordination Across Tools Based on User Story

As shown in Figure 12 [51], there can be a very large set of tools that can be used to support analysis and develop the needed data and information across all of the domains. Notionally the Reference Technology Platform (RTP) [6] is the collective set of tools that an organization has in their inventory. Any specific program creates a RTP instance. A key challenge is integrating the assembled tools, especially when they may not have been created to be integrated, and equally important is that the methods for assembling and using these analysis workflows is largely in the heads of a few subject matter experts, as explained by our sponsors. Therefore, it is important that appropriate methods are applied to the selected tools that are assembled for use on a project or program. As a secondary objective that is being demonstrated as a leading-edge approach by NASA/JPL is to ensure models are created that comply with established modeling patterns that have been formalized using ontologies. We provided information on the NASA/JPL approach, which transforms the model information into a tool-neutral AST based on ontologies, and then uses standard SWT to apply checks to ensure completeness and consistency [86].

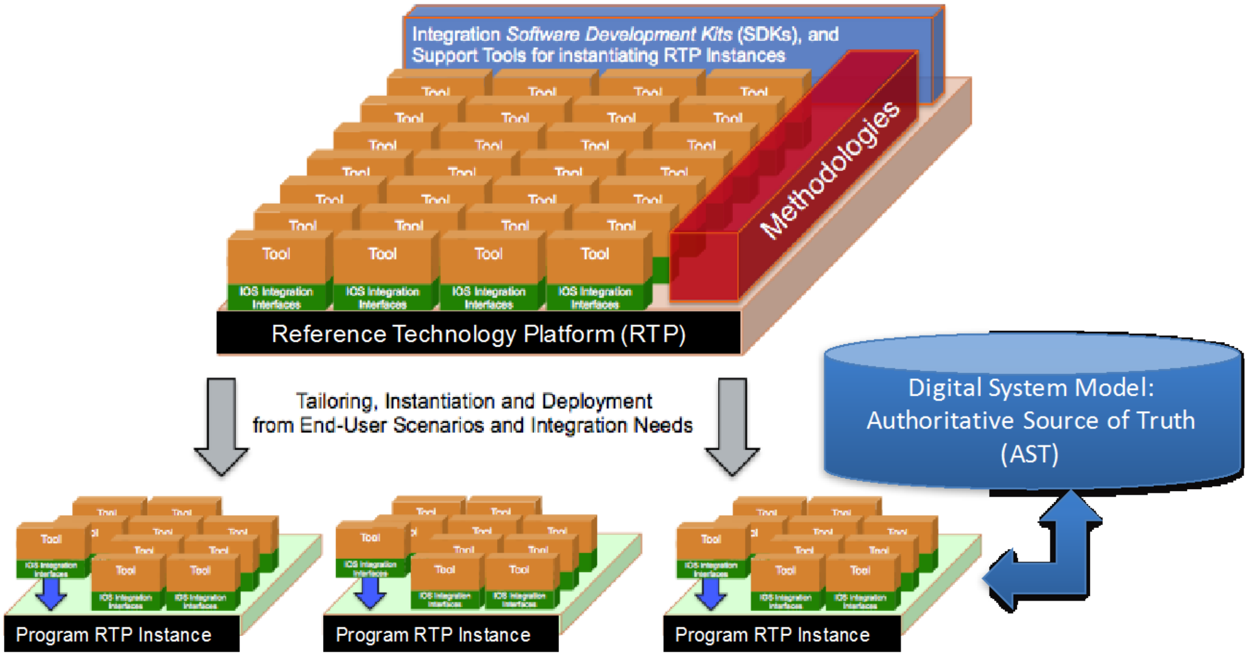


Figure 12. Appropriate Methods Needed Across Domains

4.2 SEMANTIC WEB TECHNOLOGIES AND ONTOLOGIES

Briefly, the SWTs are based on a standard suite of languages, models, and tools that are suited to knowledge representation. Figure 13 provides a perspective on the SWT stack, which includes eXtended Markup Language (XML) [115], Resource Description Framework (RDF) [163], Web Ontology Language (OWL) [162] (i.e., OWL2), the SPARQL Protocol And RDF Query Language (SPARQL) [163], and others. RDF can describe instances of ontologies – that is, the data for particular model instances, where OWL relates more to metamodels describing the class of information and relationships that can be characterized as RDF instances. The SWT was created to extend the current Internet allowing combinations of metadata, structure, and various technologies enabling machines to derive meaning from information, both assisting and reducing human intervention. This technology is generally applicable to many different applications, and we discuss a few in the following section.

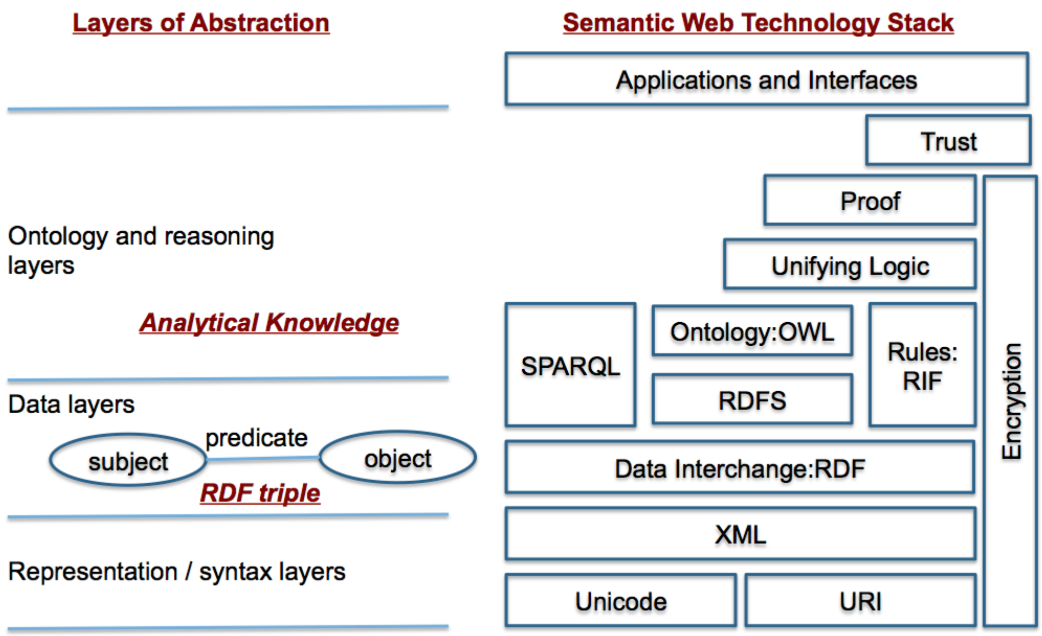


Figure 13. Semantic Web Technologies related to Layers of Abstraction

4.3 NASA/JPL INTEGRATED MODEL CENTRIC ENGINEERING (IMCE) ONTOLOGY

Our research is beginning to reflect through demonstrations and presentations some of the different uses of SWT and ontologies. The following figures have been taking from *Model-Centric Engineering, Part 3: Foundational Concepts for Building System Models* [87]. Figure 15 shows the IMCE ontology concept that is being evolved by NASA/JPL. Their process involves:

- Creating the foundational IMCE systems engineering ontologies [90] derived from modeling patterns (reflected in Figure 14), including:
  - Mission ontologies
  - Project ontologies
  - Analysis ontologies
  - The rationale underlying these ontologies are currently being documented by NASA/JPL's Steve Jenkins are part of a new effort called the Semantic Technologies for Systems Engineering Foundation [151]
- The ontologies can be created with any OWL modeling tool such as the open source Protégé [128]
- The ontologies are transformed into SysML profiles [89]
- The SysML profiles are loaded into a modeling tool (MagicDraw in this case) for creating models
- The profiled SysML models are exported back into OWL statements
- Checks for completeness, consistency and well-formedness can be performed

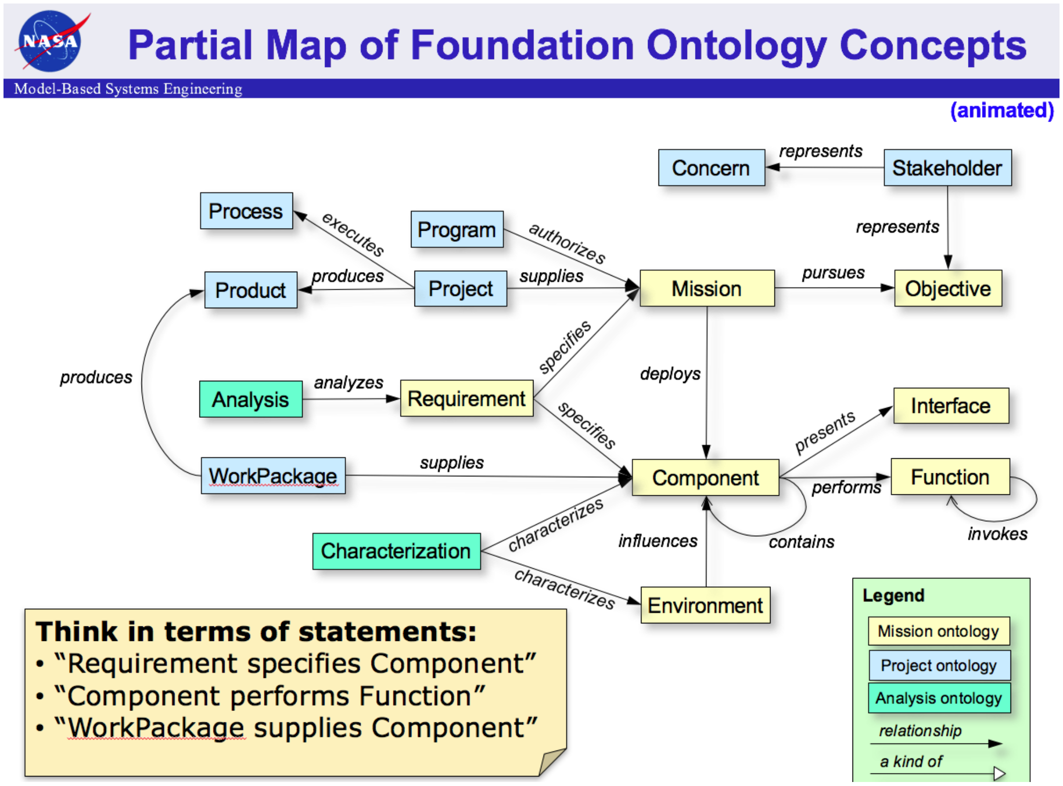


Figure 14. NASA/JPL Foundational Ontology for Systems Engineering

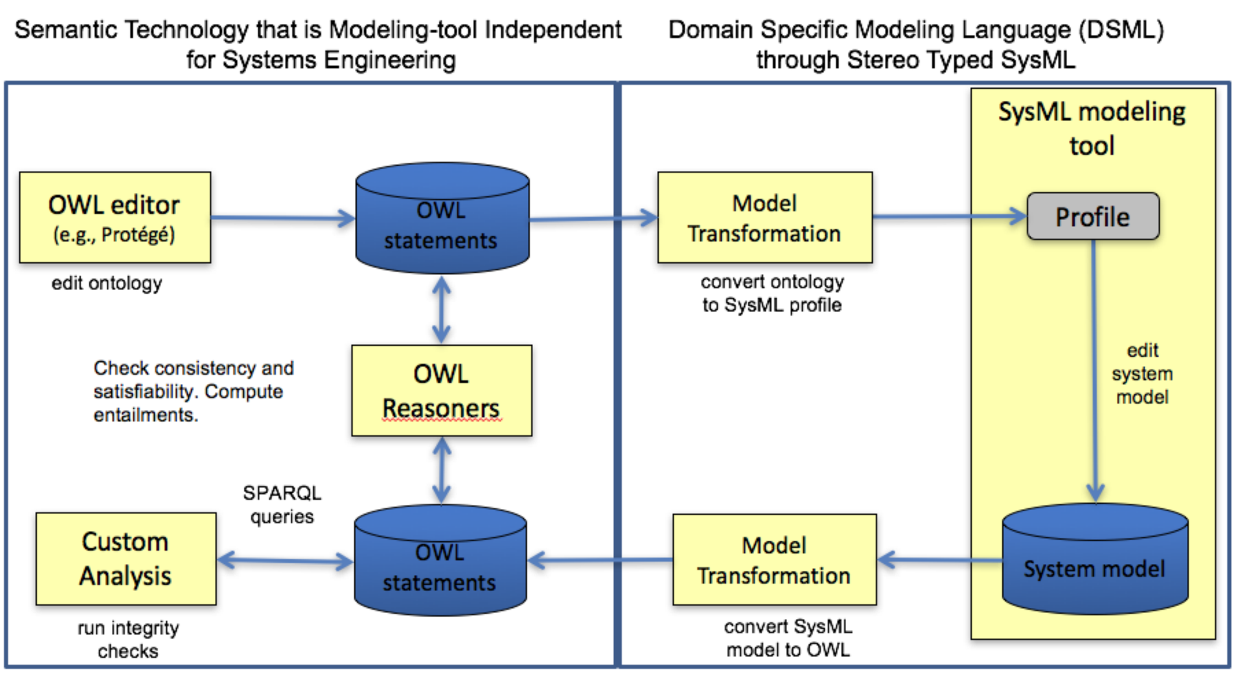


Figure 15. From Ontologies to SysML Profiles and Back to Analyzable OWL / RDF

Figure 16 shows the various representations associated with the concept described in Figure 15:

1. The modeled statement in English is: "Component performs Function"
2. The OWL/RDF representation of the statement in low-level XML for this same statement

3. The Profile and Stereotypes used in the model (loaded into a SysML model)
4. The Stereotypes used in a SysML Block Definition Diagram (BDD) – while SysML is the graphical language that is used, the stereotypes derived from the ontologies effectively make the use in SysML into a Domain-specific Modeling Language

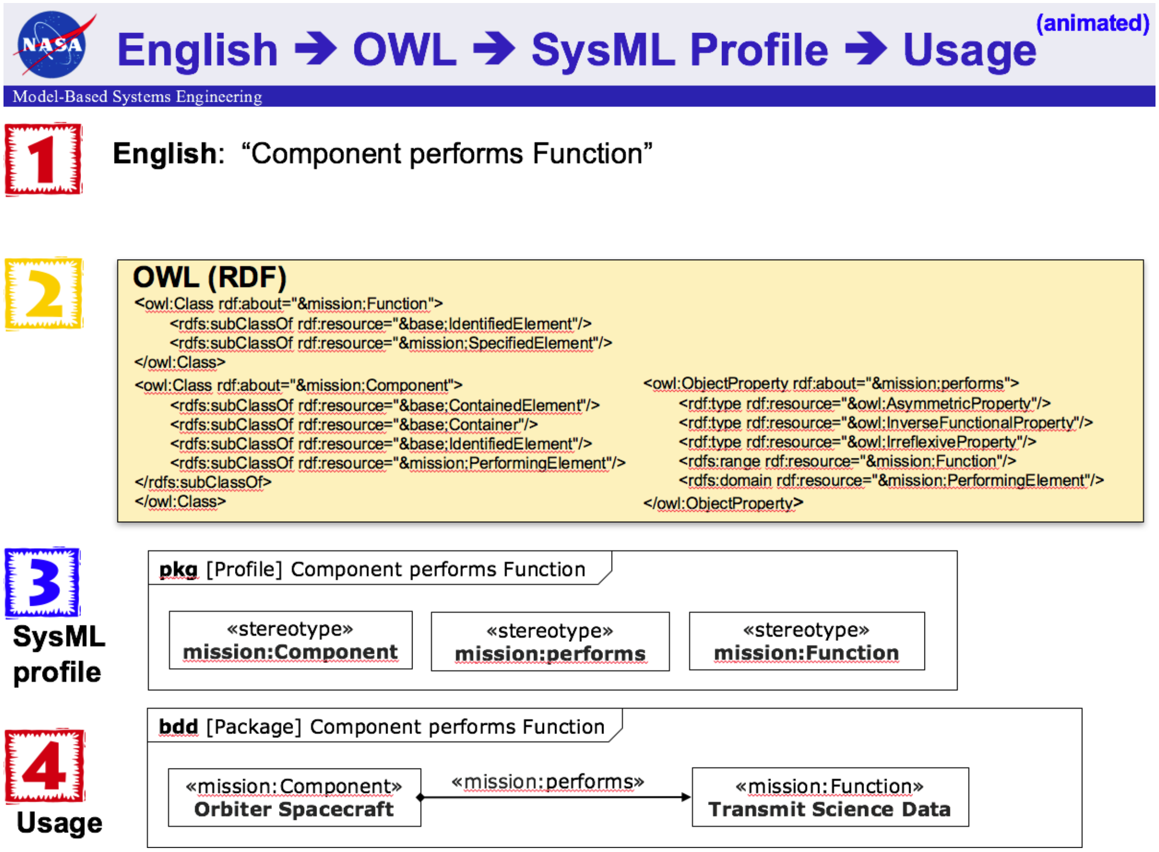
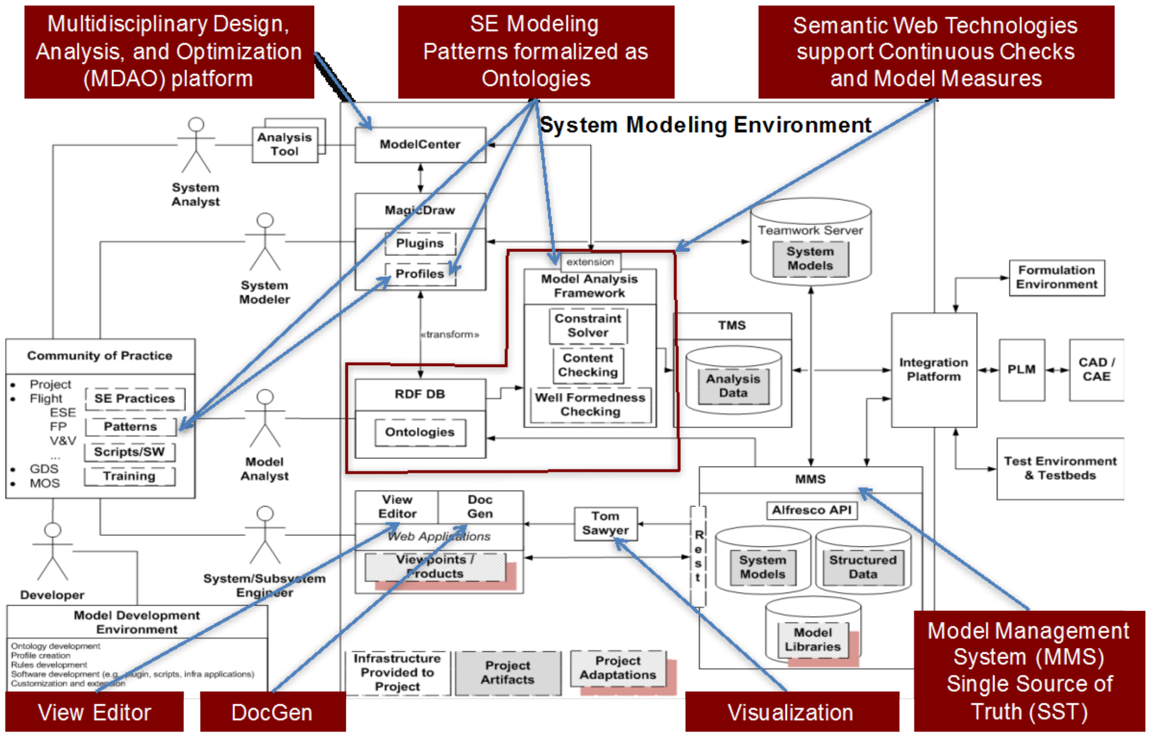


Figure 16. Multiple Representations in Process

Figure 17 provides another perspective showing where these SWT would reside architecturally using an instantiation created by NASA/JPL of OpenMBEE. A number of the components we are interested in using, include:

- The NASA/JPL IMCE ontologies for systems engineering, highlighted in the center of the figure, are used to check constraints (e.g., consistency, completeness, well-formedness) [86] [87] related to the model as shown in Figure 14
- Three core elements of OpenMBEE are: View Editor, Model Development Kit (MDK)/DocGen and Model Management System (MMS); note OpenMBEE can be used without the JPL-IMCE ontologies [90]
- MagicDraw client (in which the MDK/DocGen) plugin works
- Teamwork Cloud server from NoMagic is used with MMS



*An Integrated Model Centric Engineering (IMCE) Reference Architecture for a Model Based Engineering Environment (MBEE), NASA/JPL, Sept, 2014.

Figure 17. NASA/JPL Instantiation of OpenMBEE (circa 2014)

4.4 Digital Environnent at Airbus Space

We have discussed the importance of an underlying information model (e.g., ontology) to enable the cross-domain integration of information in an AST [23]. The concept of semantic analysis that is integrated within the Integrated Modeling Environment (IME) is not limited to NASA/JPL. Ralf Hartmann, the Vice President of Enterprise Digitization for Airbus, gave a presentation at the NASA/JPL Symposium and Workshop in Jan 2017 [75]. While there were many points made in this presentation, of particular interest was a historical perspective on how they have been assembling a system design engineering environment to cover the entire lifecycle. The representation of the environment as shown in Figure 18 was particularly interesting as it relates to the concept of a semantically rich information; this pertains to the box in the middle call RangeDB Data Management. This is a relatively recent development where they replaced a commercial product with their own infrastructure functionality (i.e., “secret sauce”) that provides a Semantic Data Model for multi-disciplinary Integration as shown in Figure 21. We did discuss this with a person from Airbus at the event, and asked about the strange name (i.e., RangeDB), and he said it was “historical.” This effort confirms why we believe SWT will play a key role to characterize the underlying information model for both ARDEC and NAVAIR, and again reflects positively on the NASA/JPL use of SWT as discussed in this section.

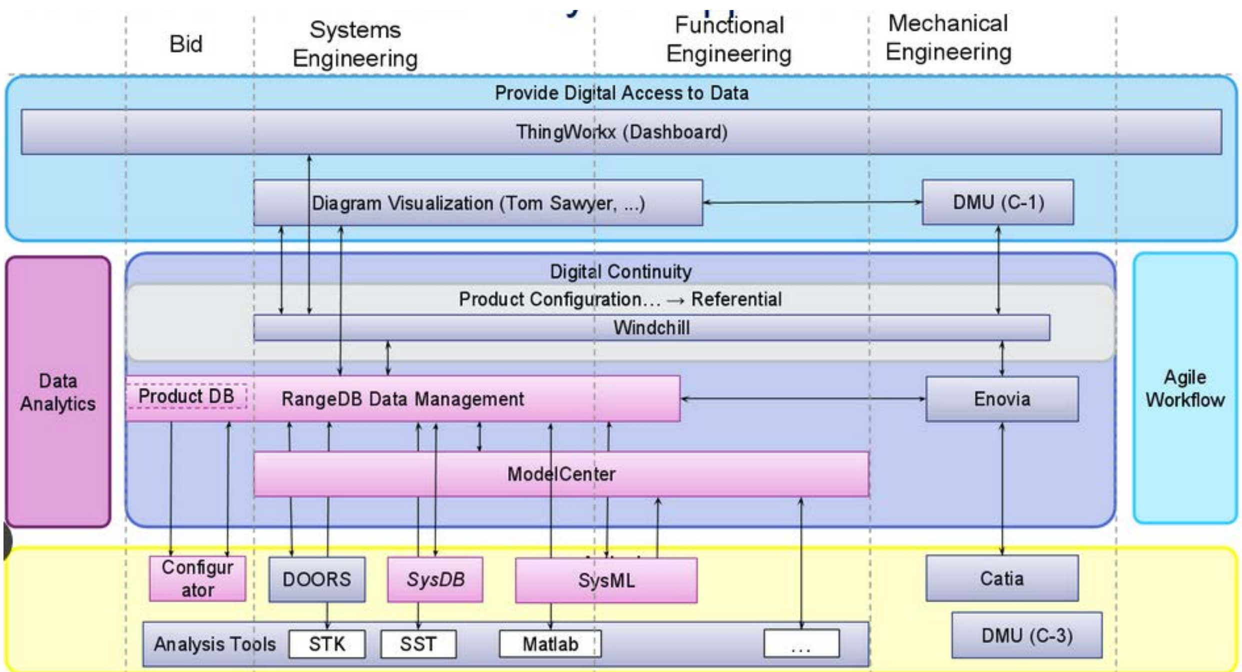


Figure 18. Airbus Digital End-to-End (System & Product) Engineering

Finally, the Hartmann briefing also included an associated roadmap as shown in Figure 19 that was structured in two dimensions:

- Technology clusters
    - Requirement engineering & V&V
    - MBSE and design
    - Engineering data lifecycle management
    - Collaborative engineering
- System engineering technology integration levels
    - Data integration (just connecting data)
    - Semantic integration (identifies rules how to connect and understand data)
    - End-to-end (knowledge management)

The key reflection on this roadmap is acknowledging the increased need to formalize the underlying information model as we move to the right (i.e., future), which can exploit more computational automation such as computational intelligence (i.e., AI, machine learning, etc.), enabled by high performance computing.

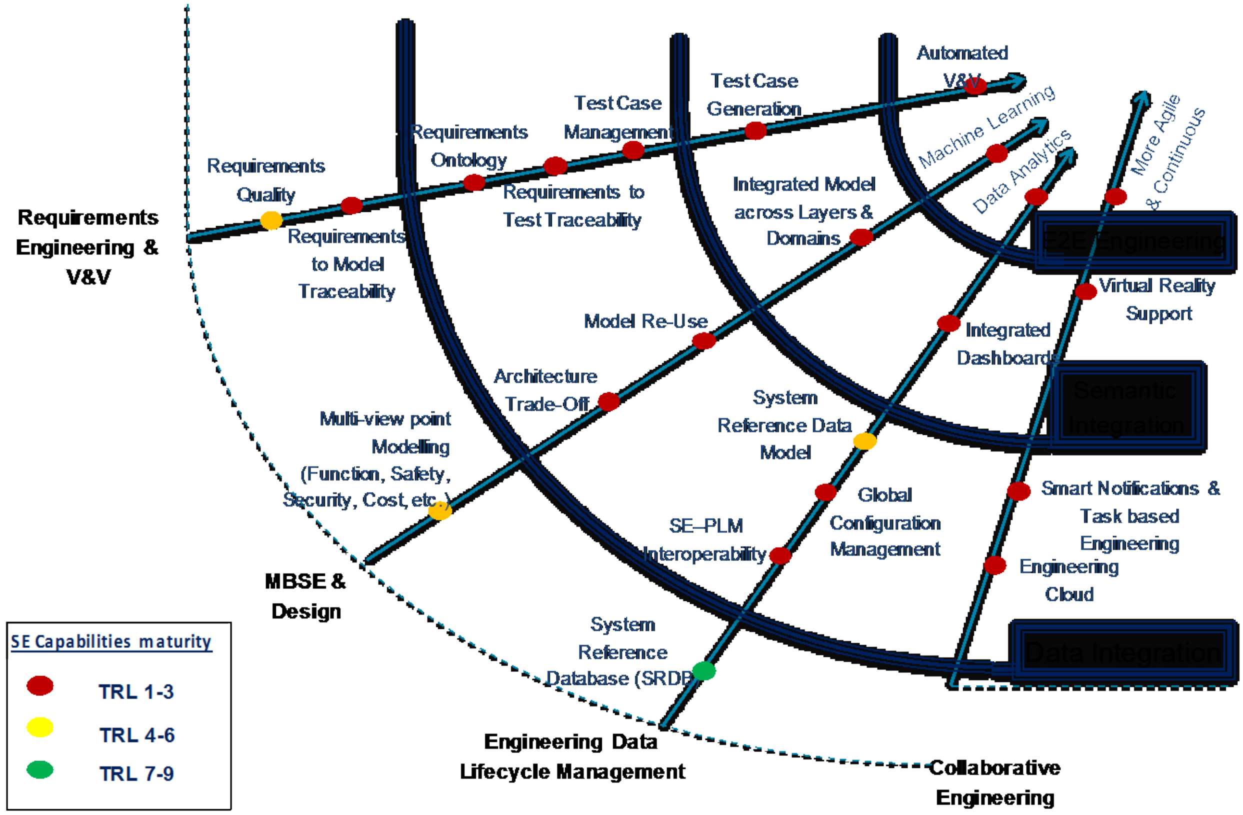


Figure 19. Airbus Roadmap Shown Bands of Digital Engineering Integration

4.5 Integration and Interoperability Framework (IoIF)

Our instantiation of an Integrated Modeling Environment (IME) to support what has been discussed in the context of the use of SWT by JPL-IMCE within OpenMBEE and the Semantic Information Model of Airbus's IME is IoIF. This is an evolving part of our research, but we have executed demonstrations of IoIF as reflected in Figure 20. This example of the IoIF uses two active models and passes published data through the SWT layer before delivering the data to the subscribing model. The published data that is passed into the SWT is extracted in different units and by different name. The example demonstrates the ability of the IoIF to convert both units and name, through the following steps:

- SysML model includes model with a specific instance of linear speed
- DocGen transforms SysML model data to xml format
- Proxy A captures and transforms xml data to RDF
- Proxy A publishes linear speed (in m/s) to Data Acquisition and Aggregation (DAA)
- Linear speed variable name and units will not match what is needed for Proxy B
- Mission Model Proxy B subscribes to red team linear speed
- DAA handles publish and subscribe from proxies
- SWT resolves the differences in the variable naming of linear speed and also the units
- When Proxy A (DocGen) publishes a new linear speed then the DAA initiates a request to the SWT to get the needed information for the subscribers of that data (Mission Model) and sends the updated information to the subscriber (Mission Model)
- DAA stores RDF instance data

- For the Demo, the team manually changed SysML model's linear speed and re-ran Mission Model simulation to demonstrate automated propagation of data change through system

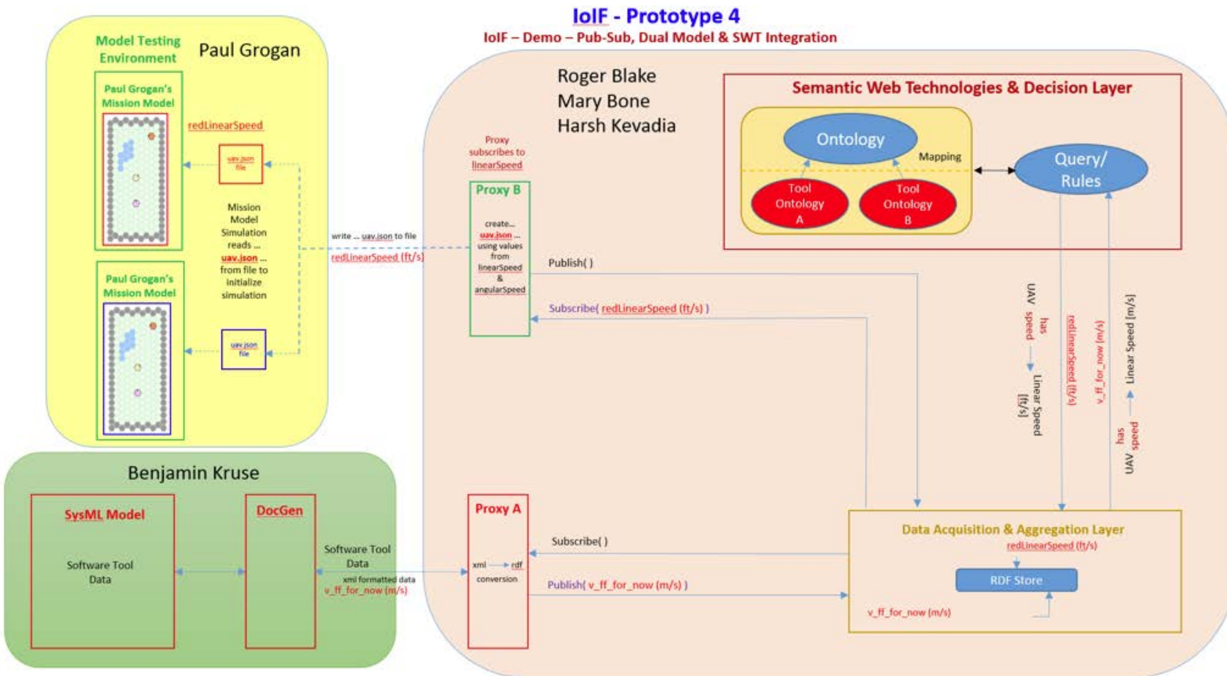


Figure 20. Integrating System Model Data through SWT to 2D Simulation

Evolving updates on IoIF, as reflected in Figure 21 continue to focus on SWT, including, relationships between OpenMBEE, Model Management System (MMS), View Editor, in the instantiation of Docker [62], which are now running an Amazon Web Service (AWS) as reflected in Figure 22. This capability was initially rolled-out in mid-February 2018, and more information and its use will be provided in future technical reports.

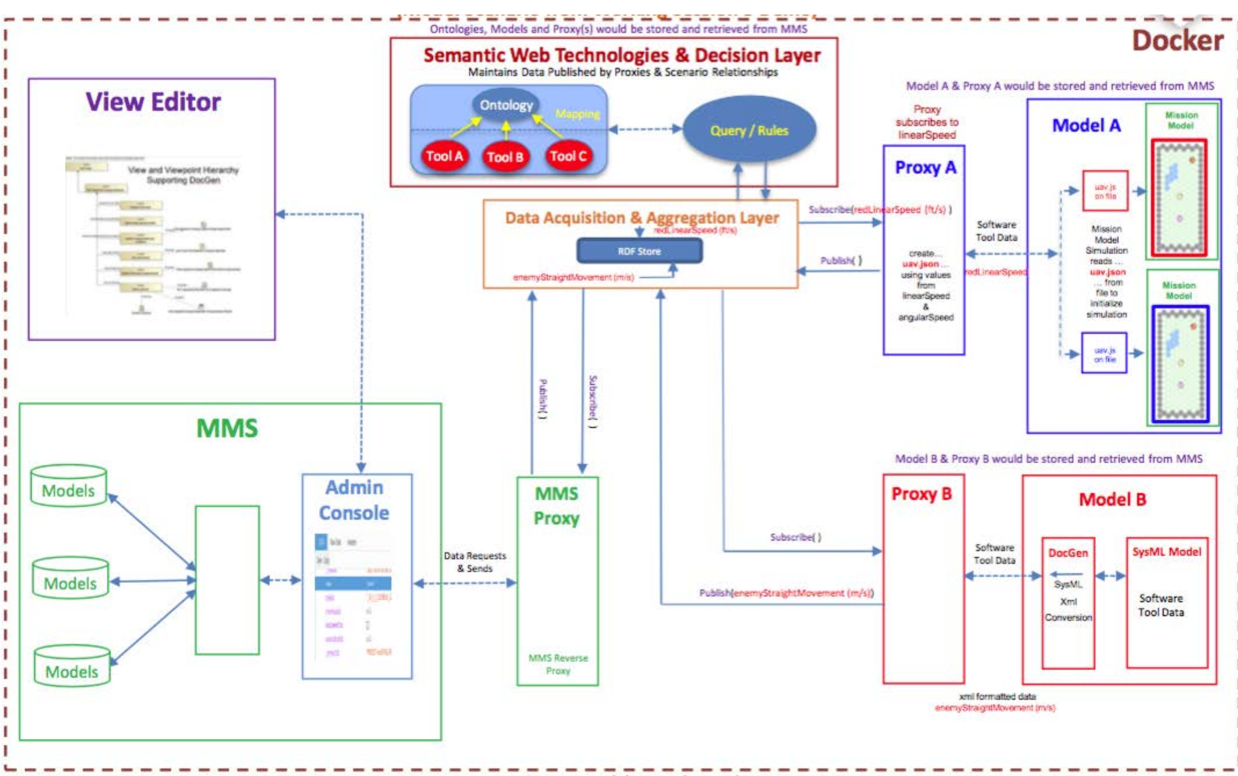


Figure 21. Integrating and Interoperability Framework (IoIF)

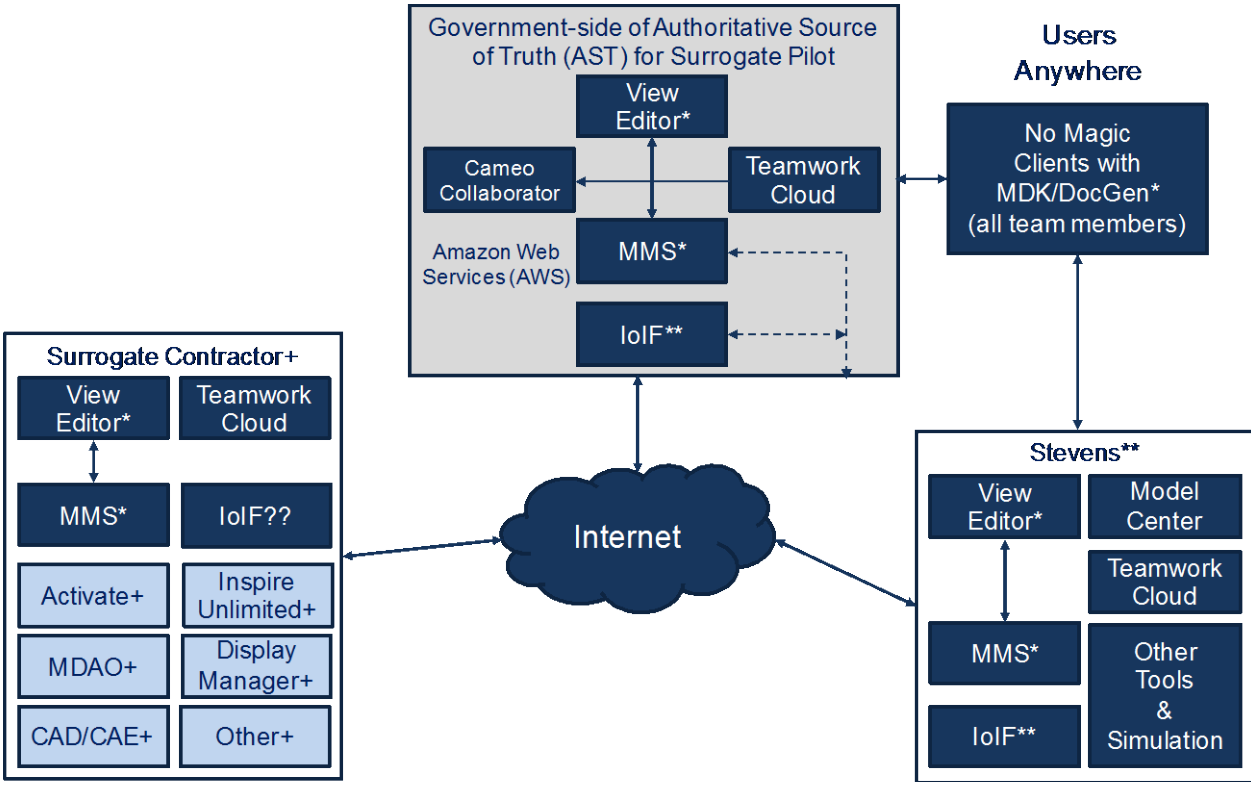


Figure 22. Elements of Authoritative Source of Truth – Including IoIF, MagicDraw, MMS, View Editor, Teamwork Cloud and Various Software Tools

4.6 Cross-Domain Integration and Natural Language Process of Requirements

Drs. Mark Austin and Leonard Petnga from University of Maryland (UMD) discussed their work at a NAVAIR working session on Systems Integration Capability using Semantic Modeling of Requirements, Components and Architectures. Mark discussed the concept and showed the results of a demonstration for some sample requirements his student provided from NASA Goddard. Leonard discussed the use of SWT for decoupling of architecture and component domains. Leonard also provided an example to automate the generation and checking of valid component relationships. The increased focus on SET has caused us to stop on this investigation.

4.7 Ontology Derived from System Engineering Technical Review (SETR) Handbook

Dr. Mary Bone started the development of an ontology for the classes of information described in the SETR Process Handbook as shown in Figure 24. We have not continued this work, because we are unsure how the SETR reviews will be used under the new concept being explored in the surrogate pilot.

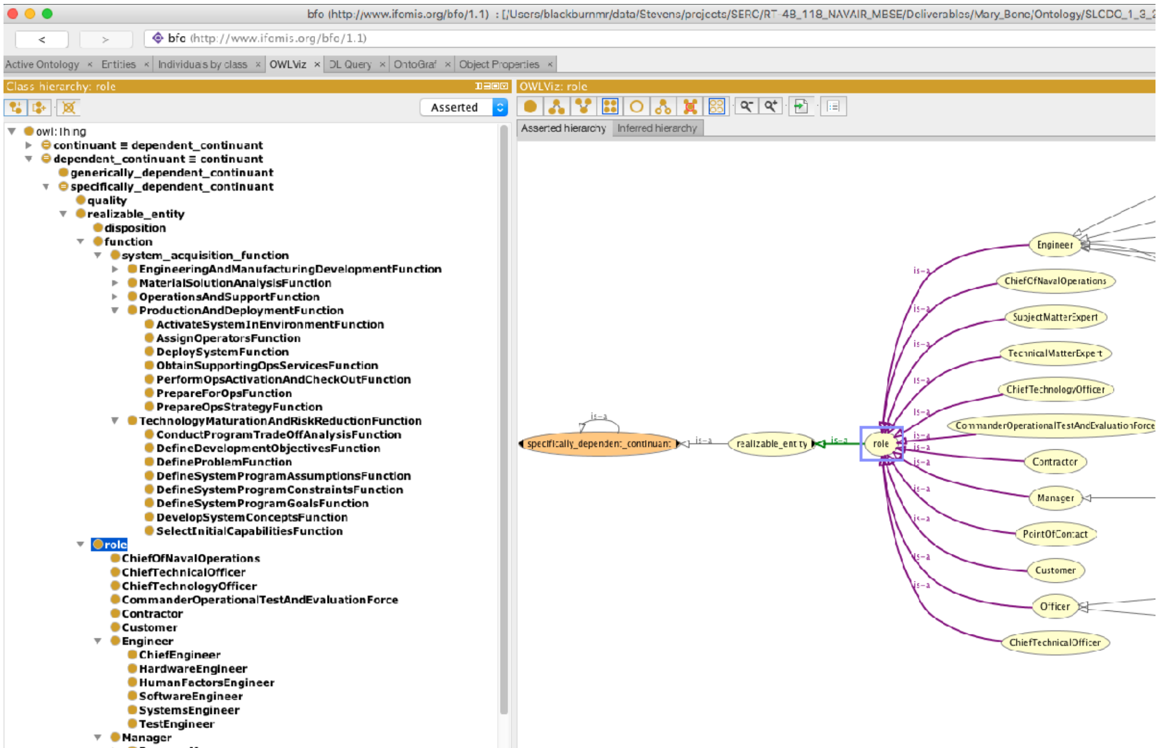


Figure 23. Class Structure for Ontology Derived From SETR Process Handbook

4.8 DECISION FRAMEWORK RELATED TO CROSS-DOMAIN INTEGRATION

Working with our ARDEC sponsors and collaborators, we have advanced the concept of the Decision Framework and demonstrated the technical feasibility of capturing needed input information from models. Dr. Matt Cilli is in the process of producing a journal paper so that the computational algorithms underlying the Decision Framework will become public domain, which should allow us to use this concept with NAVAIR and other research sponsors.

The unique research approach is to use SWT to demonstrate the concept to both characterize the underlying data and information, as well as rules, and query language for processing and data exchange. Several briefings on SWT concepts and example uses have been provided in both working session and webinar sessions.

We will investigate this as a basis for an objective approach to assess design maturity based on an ontological representation of the system using standards-based SWT. This will provide the means for assessing completeness and consistency across different models, developed using different languages and methodologies. This will leverage SWT for creating an ontology to demonstrate concepts for reasoning about conceptual models and design model maturity, which is tool neutral.

Figure 24 provides a perspective on a standard systems engineering flow to illustrate where the Decision Framework fits into the overarching analysis workflow:

- CONOPS derived from simulation and gaming technologies are used to look at scenarios for trade space analysis of mission alternative
- "What" we want – requirements and constraints for a system of System of Systems (SoS) mapping back to the mission requirements
- "How" (1 or more) – designs to achieve the "What"

- “How well” (usually many) to assess the “How” using analysis, testing, reviews and assessing how the design satisfies the requirements, given the constraints to achieve the mission concept
- The underlying Information Model (ontology) links the data or metadata from many different domains
- The Decision Framework, we believe can demonstrate how data from the information model can be used to populate the Decision Framework

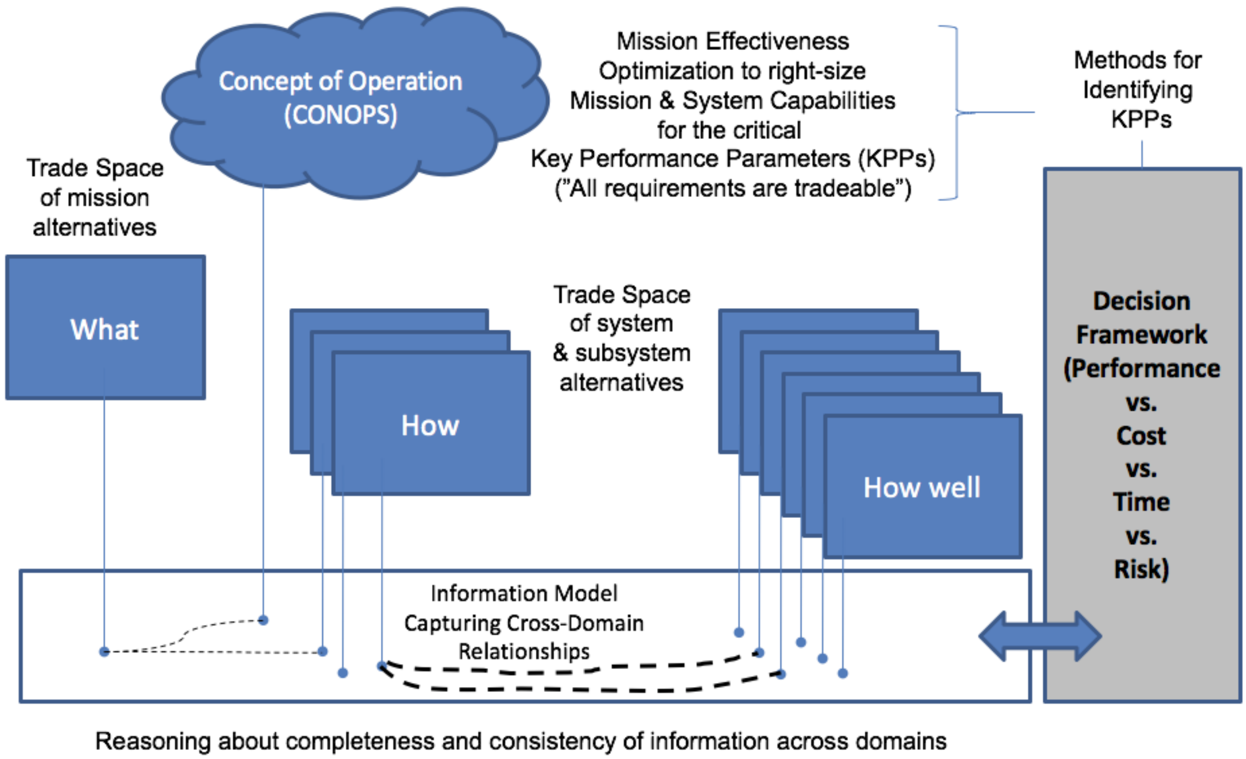


Figure 24. Context of System Engineering of Challenge Areas

As discussed in the next use case, we have developed using Phoenix Integration’s ModelCenter [125] and MBSEPak, with SysML a way to formalize some of the inputs needed for the Decision Framework.

5 UC01: MULTIDISCIPLINARY DESIGN, ANALYSIS AND OPTIMIZATION (MDAO)

This use case investigates various uses of Multidisciplinary Design, Analysis and Optimization (MDAO) at the mission, system and subsystem levels, which provides a means for continual assessment of trades (i.e., analysis of alternatives) to support KPP assessment; this also relates to representations within system models. This use case also investigates the methods to trace capabilities to the relevant design disciplines and perform cross-domain analyses through MDAO for problem and design tradespace analyses. In addition, to characterizing elements of the framework, cross-domain relationships, but also characterize the methods used to support MDAO in a tool independent manner.

MDAO is an approach for calculating optimal designs and understanding design trade-offs in an environment that simultaneously considers many types of simulations, evaluations, and objectives. For example, when designing an air vehicle, there is typically a trade-off between maximizing performance and maximizing efficiency, where calculating either of these objectives require multiple disciplinary models (geometry, weight, aerodynamics, propulsion). MDAO prescribes ways to integrate these

models and explore the necessary trade-offs among the objectives to make a design decision. While the theoretical foundations of MDAO are well-established by academics, a number of barriers to practical implementation exist. Chief among these is the lack of model integration, which prevents designers of one subsystem from easily assessing how changing a design variable affects the results of other subsystems' models or simulations.

As illustrated by some of the examples shown below, we can extract the key parameters in these various mission and system simulations. These parameters are fundamental to the MDAO workflows. We need to combine those parameters for different elements of a workflow, but we must also characterize our KPPs; for example, a surveillance UAV range or endurance (e.g. number of hours of flight) would be examples of possible KPPs. These KPP are modeled as the outputs from running the MDAO through different optimizations. The other aspect of the method involves identifying the constraints that must be characterized with respect to KPPs (i.e. outputs) with respect to selected inputs.

5.1 MDAO Objectives

The following provides more specific objectives for MDAO use:

- Assessing the impacts of individual design changes on system capabilities
- Supporting early-phase (conceptual design), system-level trade-off analysis using previous evaluation results from existing models
- Develop strategies to transform the contracting process so that requests for proposals (RFPs) can be designed more flexibly toward value-based (rather than target-based) design

In pursuit of these objectives, the research activities entail:

- Develop generic multidisciplinary models of NAVAIR-relevant system examples, including analyses of the geometry, structure, aerodynamics, propulsion, and performance capabilities, to be used as an example case
- Explore using systems representations (e.g. SysML, Domain Specific Models) to map all inputs (parameters and variables) and outputs (objectives, constraints, intermediate parameters) among the individual models
- Conduct trade studies on the UAS design using established approaches and tools for MDAO, exploring different approaches, tools, and visualization techniques to most effectively display information and uncertainty for decision-makers
- Explore ways that previous trade study results on detail-phase product design can be useful toward new conceptual design of products with varying mission capability requirements
- Use the surrogate pilot to understand the barriers to implementing this type of MDAO, culturally and practically/theoretically
- Explore more general ways to map and coordinate subject matter experts (SMEs) and data, models, and meta-models for improved requirements setting for RFP or CONOPS, and value-driven design
- Explore the ways that MDAO and MBSE tools can work together

One of the objectives of this project is to leverage the most powerful tools that are often used by industry as well as government organization. We have secured academic licenses to Phoenix Integration's ModelCenter [125]. Further, while research to date examines the use of MDAO at the systems level. We have received additional academic licenses to ModelCenter to investigate the use of MDAO at the mission and subsystem levels. However, based on the concept of the SET Framework,

MDAO analysis at the subsystem level will probably be carried out by industry that is developing the designs.

5.2 MDAO METHODS

Using tools like ModelCenter, we have investigated, demonstrated and described methods for applying such tools, and also identified relevant research questions in the context of those advanced tools. For example, the steps for an MDAO method may be characterized as:

- Describe a workflow (scenarios) for a KPP (e.g., range, notionally similar to surveillance time)
- Determine relevant set of inputs and outputs (parameters)
- Illustrate how to use a Design of Experiments (DoE) and use analyses such as sensitivity analysis and visualizations to understand the key parameter to use with optimizations
- Illustrate Optimization using solvers with key parameters and define different (key objective functions – on outputs) to determine set of solutions (results often provided as a table of possible solutions)
- Use visualizations to understand relationships of different solutions

A number of methods can be applied to formulate multidisciplinary optimization problems, develop useful surrogate models, and calculate optimal and Pareto-optimal solutions. Optimization problems can be formulated with a number of different objectives by converting some objectives to targets or constraints, summing the objectives with value-based and unit-consistent weighting schemes, or multiplying and dividing objectives by one another. Surrogate models are often used to quickly simulate the behavior of a more computationally-intensive simulation model, and some common methods include interpolation, response surface using regression models, artificial neural networks, kriging, and support vector machines. Finally, numerical optimization can be performed using a number of different algorithms and techniques, including gradient-based methods, pattern search methods, and population-based methods. For each of these, different techniques have been found to be more suitable to different applications, and part of this research directive will be to identify and demonstrate the best tools for this MCE architecture.

5.3 INTEGRATIONS WITH RELATED TASKS

Through this project, and the creation of an MCE architecture that follows an AST and a consistent ontology, we investigate how to leverage MDAO techniques in the design decision-making process. A solid framework for MDAO can enable multi-objective optimization, showing product developers how different design objectives compete with one another. For example, we know that improving an objective like “minimize weight” typically requires a sacrifice in the objective to “maximize power.” The magnitude of that improvement-sacrifice relationship, which often involves different units and requires human judgement to make a mission-appropriate decision, can be revealed by combining different simulation models, surrogate models, and optimization routines. As this may involve balancing a large number of objectives, one of the key challenges is in visualization of the results to enable informed decision-making. This fits into all five tasks of the project, as the entire information architecture must be built to support cross-disciplinary analysis, and specific tools and techniques can be integrated and tested at different stages of the transformation.

5.4 MDAO UAV Examples and Use Cases

Examples and demonstration covering several of the objectives have been presented in several working sessions as well as several bi-weekly status meetings. We have four use cases:

1. Developing MDAO workflows for KPP examples at system level
2. ModelCenter integrated with a Graphical Concept of Operation (CONOPS) example using Unity gaming engine at the mission level
3. Integrating MagicDraw SysML models with ModelCenter and MBSEPak for an underwater super cavitating modeling system
4. ModelCenter and MBSEPak, with MagicDraw SysML to formalize the concept of an Assessment Flow Diagram, which is part of the Decision Framework and process [44]

This section provides a summary of some of the evolving use of MDAO in our research.

5.4.1 MDAO Example for Fixed Wing UAV

The first demonstrated workflow shown in Figure 25 was developed using ModelCenter. This demonstration covered several aspects of the modeling objectives discussed in this section, including:

- Describe and execute a workflow analysis of UAS capabilities (e.g., range, velocity, and fuel consumption)
- Map relationships among parameters (inputs/outputs) in disciplinary models
- Illustrate use of Design of Experiments (DoE), sensitivity analysis, and visualizations to understand capability relationships/trade-offs
- Optimize using different solvers to find sets of Pareto-optimal solutions
- Take advantage of previous model analyses for use in early-phase design with new mission capability requirements

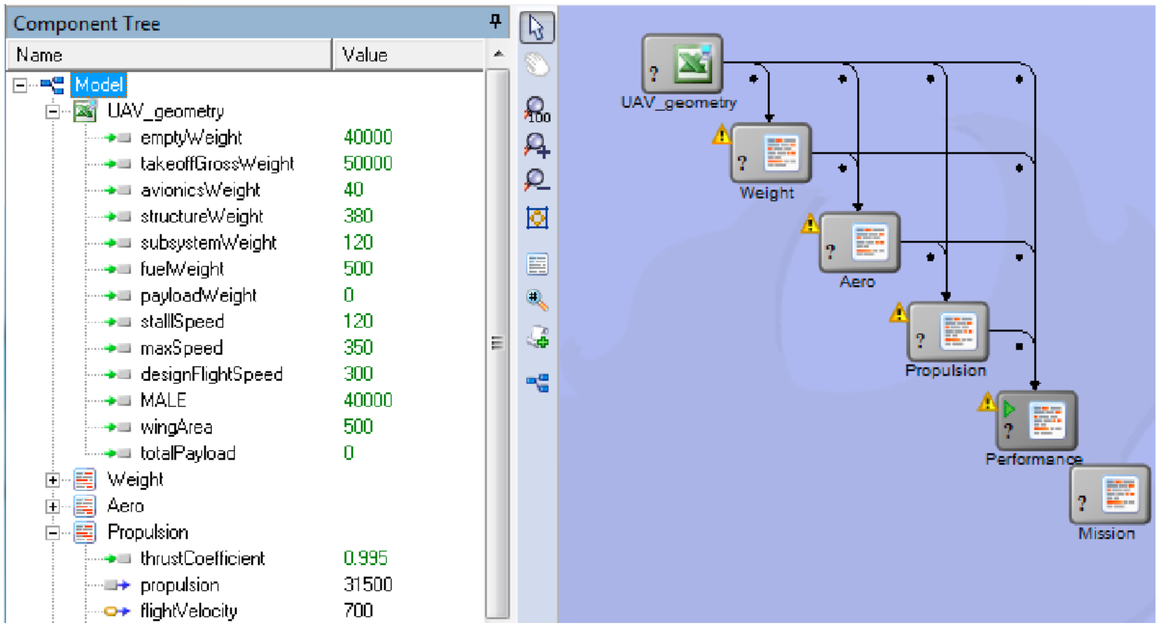


Figure 25. MDAO Example Workflow

As shown in Figure 26, the Pareto frontier (Pareto optimal set) shows the trade-off between range and propulsion. The blue points show the Pareto frontier/non-dominated solutions. The Pareto frontier was calculated using a bi-objective optimization using NSGA-II algorithm to:

- Maximize range
- Maximize propulsion
- Given 5 design variables
    - Wing area (ft2)
    - Wing span (ft)
    - Altitude (ft)
    - Speed (knots)
    - Efficiency factor

These results reflect on how much range one would have to give up in order to increase the propulsion by some amount. Based on the current set of equations characterized in the workflow, the sensitivity analysis shown in Figure 27 indicates that the wing area is the variable that exhibits the clearest trade-off. The wing span has the largest effect on range, but does not present a trade-off between these objectives.

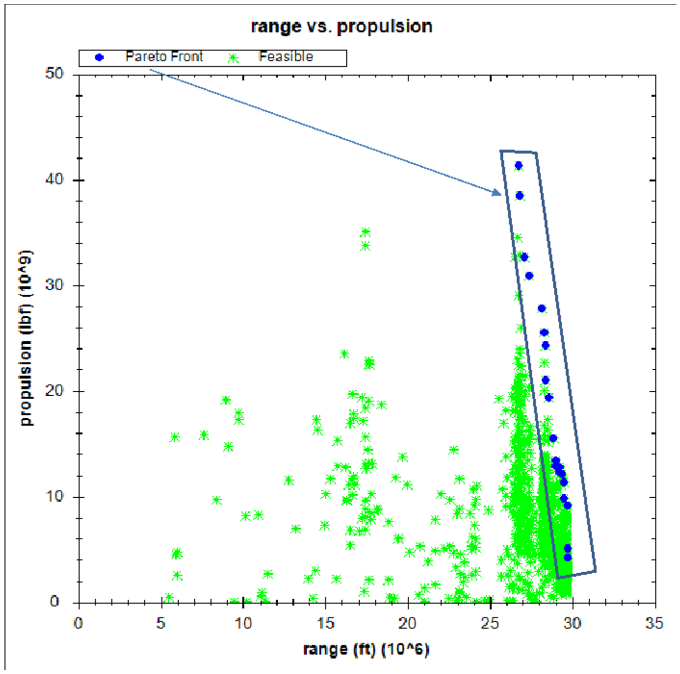


Figure 26. Pareto Frontier (Pareto Optimal Set) Shows Trade-off Between Range and Propulsion

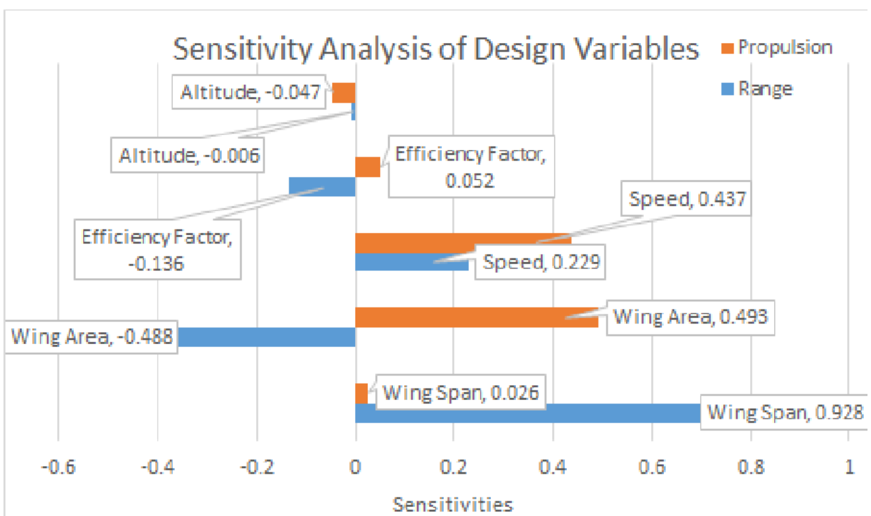


Figure 27. Sensitivity of Objectives to Design Variables

5.4.2 EXTENDING THE MDAO UAV EXAMPLE 1

Brian Chell is a PhD student working with Dr. Steven Hoffenson. Brian has produced a number of updates to the initial model. The efforts produced alternative workflows that leverage other types of solvers for different aspects of the problem including multi-physics problems. For example, one of the first steps looked at bringing SolidWorks into ModelCenter as shown in Figure 28. This provides a way to bring in detailed geometries to the analysis.

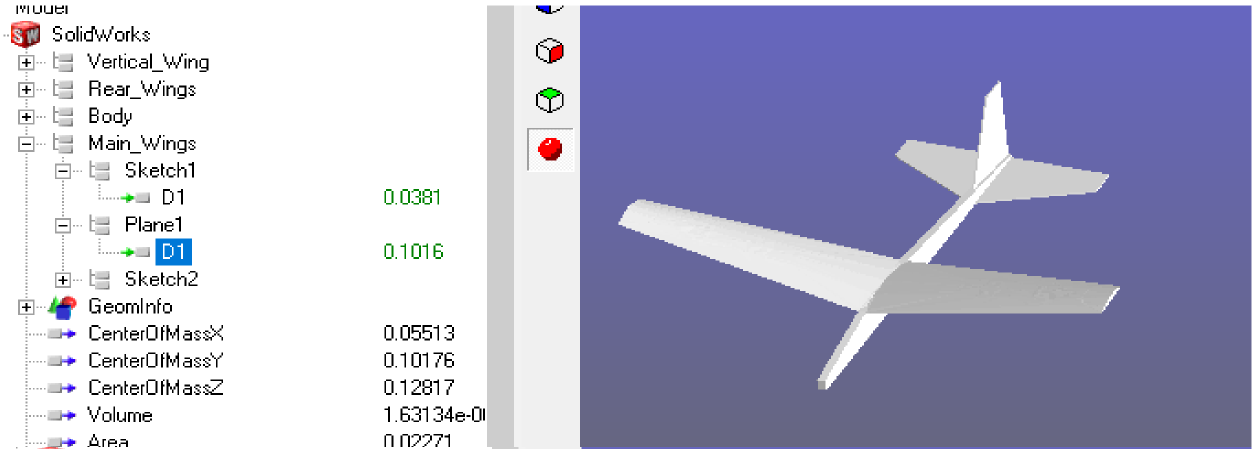


Figure 28. MDAO Workflow with SolidWords Computer Aided Design Model

There were a few challenges with the more complicated geometries, as well as:

- Open-source geometry validity is questionable
- Model variables
  - Most SolidWorks files found so far do not import variables into ModelCenter automatically
  - We assume that we can set the variables within SolidWorks, but this might be more difficult because manually setting values may not align structures (e.g., wing connect to fuselage to meeting correct)
- More complex
  - Computations solver (e.g., CFD) take longer to run on the laptops provided to students

This has led to the following investigations:

- Equation-based models derived from the model shown in Section 5.4
  - Uses DLR Institute's Unmanned Combat Air Vehicles (UCAV) [97] parameters
  - Model is fully operational
  - Based on weight fractions that are more scalable, and easier to change than DLR UCAV model
  - Model starting with payload weight vs. range vs. endurance tradeoffs
  - Looking at the potential to merge with future Computational Fluid Dynamic (CFD) results with Finite Element Analysis (FEA)
- Simulation-based models
  - Difficulties

- Still problems with importing variables into ModelCenter
  - Very large number of variables automatically imported (12,000+)
  - Under construction
- Consider open source simulation OpenVSP [119] vs. Solidworks (CFD)
  - OpenVSP is a parametric aircraft geometry tool
  - OpenVSP allows the user to create a 3D model of an aircraft defined by common engineering parameters. This model can be processed into formats suitable for engineering analysis.
  - OpenVSP commonly used with ModelCenter
  - SolidWorks has stronger analysis capabilities
  - OpenVSP is limited to a standardized shape library
  - SolidWorks Flow Simulation can handle turbulence
  - OpenVSP CFD is most valid at nominal flight conditions (e.g. low angle of attack)
  - OpenVSP should be sufficient for conceptual design phase

OpenVSP is being used for CFD. It is easier to use with limited library of shapes of quadcopters and fixed wing, and can run 'headless' (i.e., without GUI) to make computations less expensive. NASA has been using this with ModelCenter. The current status is:

- Integrated parametric geometry and CFD into ModelCenter
- Performing optimization and DOE to characterize model
- Trying to find lowest-fidelity mesh that produces accurate results
- Challenges:
  - Takes some time to change between different aircraft
  - Future NASA wrapper will make this much easier
  - High-fidelity CFD simulations are very slow on low-end laptops like those provided to students; need to determine if Stevens and provide higher performance computing resources

Figure 29 show the CFD results from the same geometry under the same flight conditions with different fidelity meshes. The simulation on the left has a coefficient of lift many magnitudes higher than the one on the right. Investigate mesh balancing accurate results and low computing cost.

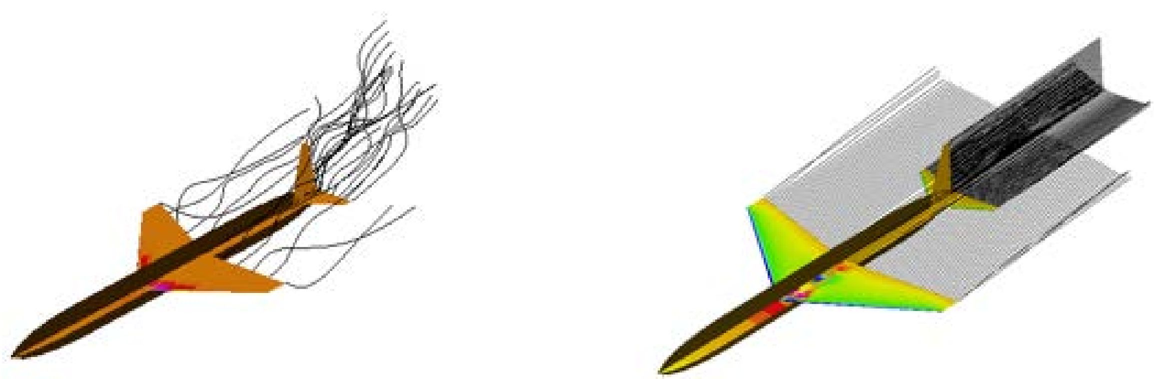


Figure 29. CFD Mesh Fidelity Importance

More recent updates include analysis for both CFD and FEA with the objective to maximize endurance and range, and minimize stress at every span-wise node. This is done with a new workflow as shown in Figure 30, with the resulting aircraft shown in Figure 31.

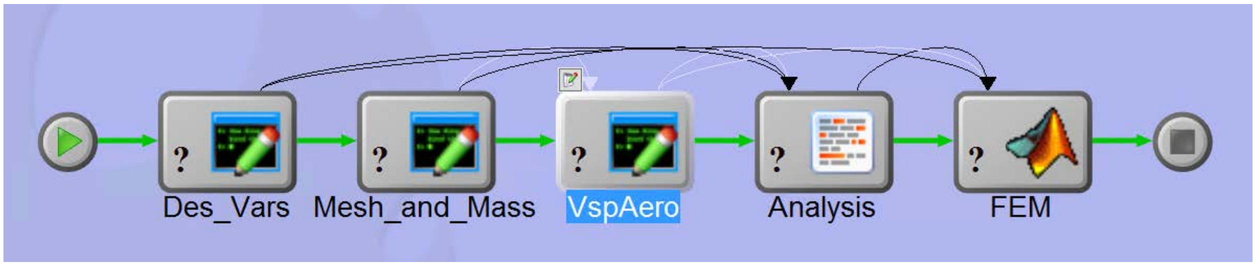


Figure 30. Update MDAO Workflow including CFD and FEA

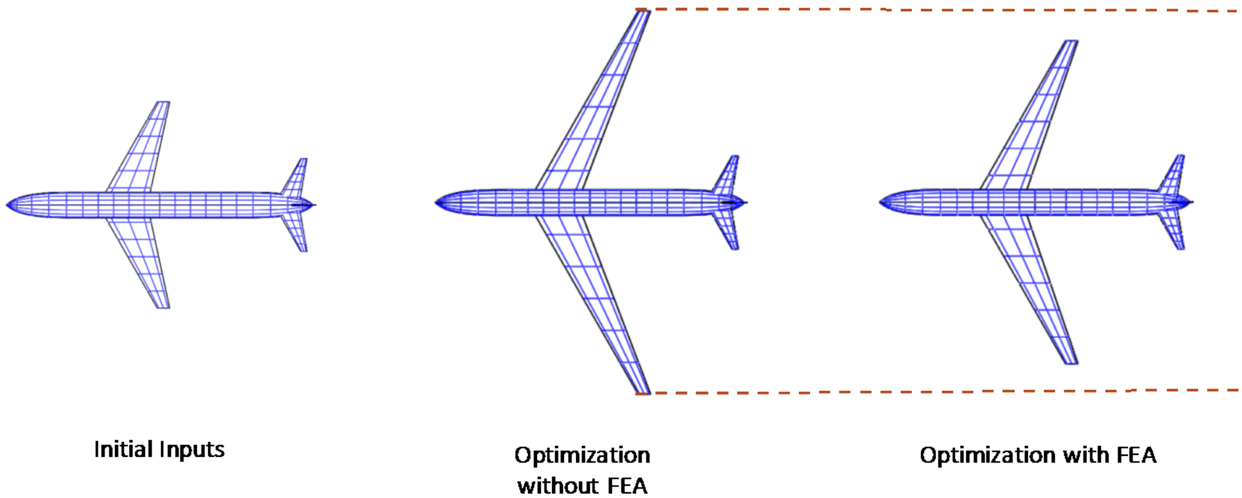


Figure 31. Resulting Aircraft Designs with and without FEA

5.5 MDAO at the Mission Level using Graphical CONOPS

This use case investigates an extension of the prior work to using the Graphical CONOPS technologies Unity gaming engine with MDAO using ModelCenter. The MDAO methods used:

- Design of Experiments (DoE) to run the simulation over the entire range of every input variable
  - Choose an appropriate DoE sampling method to shorten run time
    - Full Factorial
    - Latin Hypercube
- Sensitivity Analysis
  - Find which outputs are most sensitive to which input variables
  - Can remove (or fix the value) of non-sensitive variables to save time during optimizations
- Optimization
  - Use algorithm to optimize desired objective(s)

While there were challenges that were overcome, the experiment demonstrated that it is possible to use MDAO to optimize for mission success, and the number of experiments (runs) to cover the DoE space of 1000s cases versus 10s of cases that would be covered by running the scenarios manually.

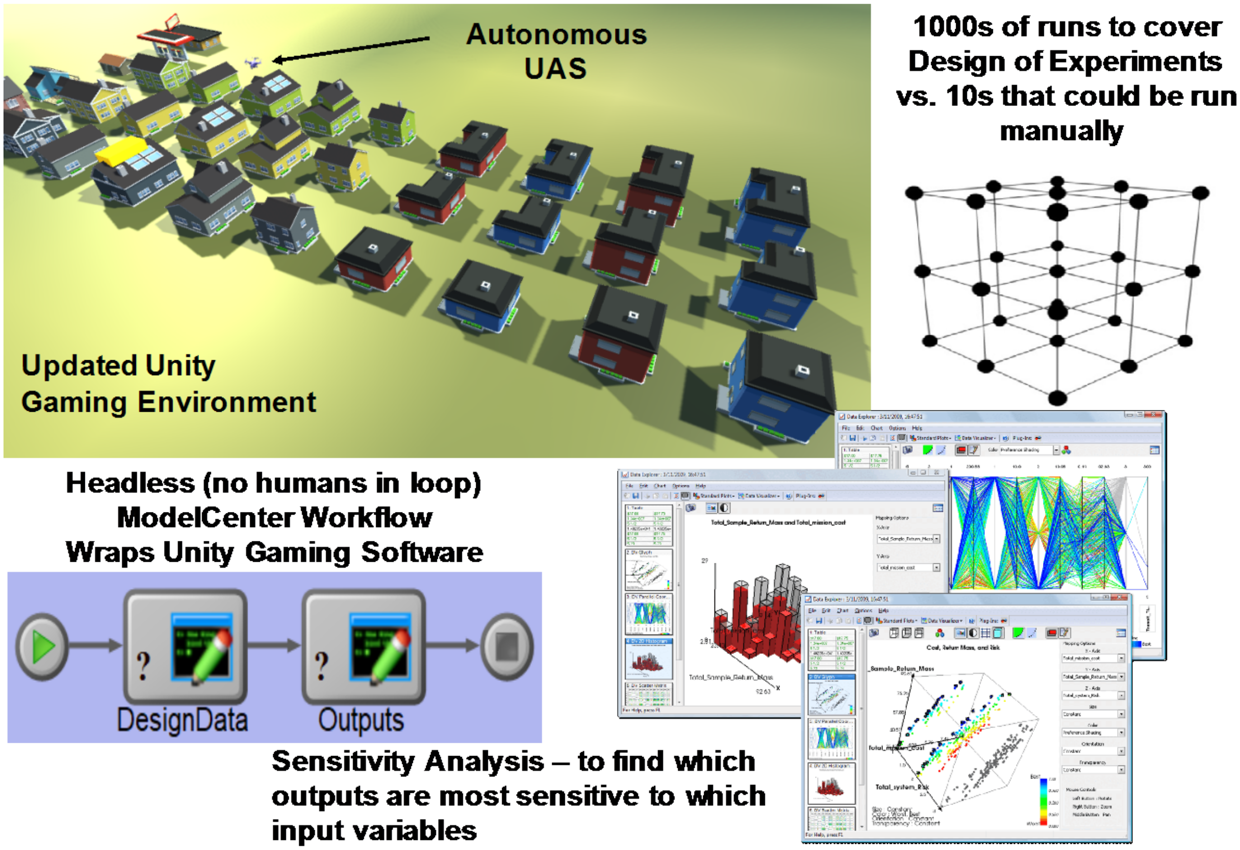


Figure 32. Explore the Integration of Graphical CONOPS Simulation with MDAO Tools

The capabilities covered focused on objective to understand and overcome the challenges for a fully automated MDAO at the Graphical CONOPS level, including:

- Performance is measured by degree of success of a mission
- Artificial Intelligence (AI) is applied to counterparties so that they can adapt to and learn behavior of system
- Full automation – there was no humans in the loop, except for validation of behavior
- Simulated environment that includes counterparties was observed to behave in a surprising manner (e.g., there was emergent behavior)
- Software communicates programmatically through file transfer – as opposed to being directed manually
- Monte Carlo results in thousands of runs (vs. 10s when run manually) are made for each initial state to provide statistics
- Simulation can run at high speed to maximize statistics and in real time to allow for human validation of simulation behavior

The finding suggests that MDAO can be used to optimize for system-level mission success to study far more trades than can be performed manually. The initial attempt created the simulation and removed the CONOPs visualization using a “headless” simulation that is wrapped by ModelCenter. Initially the architecture of the simulation was not enabled to operate in batch modes, and therefore the software had to be re-written to work with ModelCenter. When the simulation is running, the human cannot make edits, but the re-written and wrapped simulation can run thousands of design of experiments (DoE). The initial simulation ran in real-time, but a recent update now can run faster than real-time.

A time-step analysis for the new design that can run faster than real-time for the current three missions suggests:

1. The time-step is very dependent on the timescales and complexity of the mission.
2. We have initial measure of the quality of a run through the measurement of the average kinetic energy of the blue drone. The simulation fails when this number suddenly drops.
3. For our current missions, we can increase the physics time step by about a factor of two (2). This means a speedup of about a factor of two (2). This is a smaller number than was expected going into the study.
4. In physics simulations, one is often not interested in high-frequency behavior because we are interested in long-term bulk behavior of matter. In our case, we are very interested in high-frequency behavior because that behavior is used to determine the response of the agents to each other. This is like a basketball game in which players have head fakes and tells on short timescales. The defense must pick up on the short timescale events in order to respond on longer timescales.

The proposed next steps include:

1. Check the sensitivity of the speed-up with other missions. The current red drone strategy is to pursue the blue drone and interfere with it.
    - What if the red strategy was more of a zone defense?
    - What emergent surprises will we see?
    - We saw unexpected flocking behavior in the current red strategy?
2. This red strategy is very different than the one we currently have. How does this affect the speed-up?
3. Find a better measure of performance than the average kinetic energy.
4. Incorporate this into the output file so that it is convenient analysis and programmatic processing.

5.6 SysML Integration to MDAO through MBSEPak

This research investigated the use of the Phoenix Integration MBSEPak (formerly MBSE Analyzer) that provides a way to integrate MagicDraw SysML models with ModelCenter for performing MDAO analysis. Dr. John Dzielski who performed this research primarily works in Matlab, and he used an example that was familiar to him related to underwater super cavitating modeling. The process covered the following steps:

- Defining requirements models in SysML
    - MBSEPak works by adding a profile that includes a number of stereotypes to MagicDraw
    - Specify a constraint (='s), upper and/or lower bounds, and units
- Connect properties to requirements via the satisfy relationship
- Information is transferred to ModelCenter through MBSEPak plugin as shown in Figure 33
    - Requirements are shown in the Margin column of the plug-in.
    - The plug-in indicates whether the requirements are satisfied or not by a design
- MagicDraw Plug-In populates an analysis to create a workflow
    - Components correspond to constraint blocks
    - Constraints blocks are models or equations used in par diagrams
    - Constraint parameters correspond to component variables in ModelCenter
- Parametric (PAR) blocks are used to indicate to ModelCenter how to connect component I/O (values) to model values

- All of the other types of analyses discussed previous can then be applied in ModelCenter

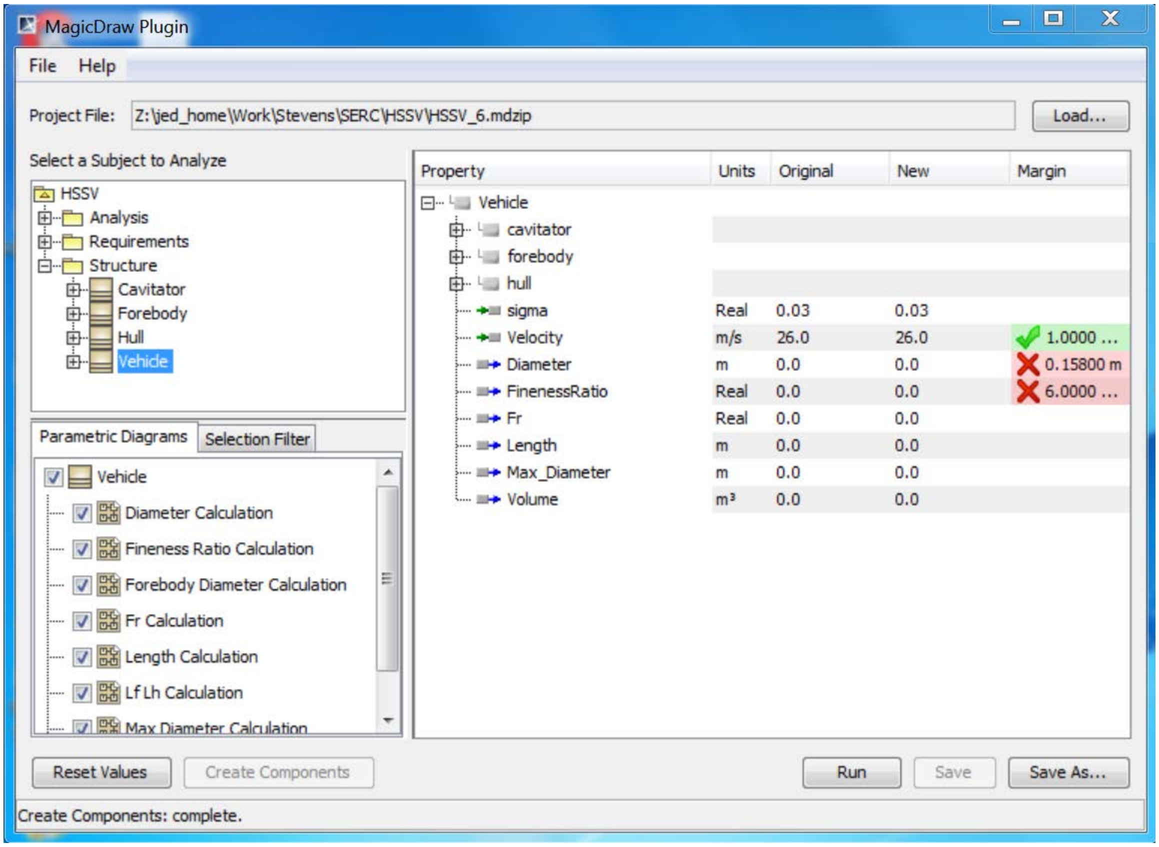


Figure 33. Example of MBSE Analyzer MagicDraw Plugin to Integrate with ModelCenter

The following reflects on some of the initial findings in his first exposure to MagicDraw, SysML, and ModelCenter:

- SysML is best used after some training
  - Even for someone skilled at modeling in Simulink, SysML has a lot of documentation, but MagicDraw can be hard to learn (but he was able to do it, on his own)
- ModelCenter is a little bit easier to understand without any training
  - Extremely flexible, anything that can be modeled in ModelCenter can be used as a constraint
  - Similar constraints will be found in other types of weapon systems
  - MBSEPak works by adding a profile that includes a number of stereotypes to MagicDraw
- It is easier to model in SysML and use the MBSEPak than to create the ModelCenter workflows manually
- ModelCenter does not understand generalization relationships as represented in SysML

5.7 Formalizing Assessment Flow Diagrams as MDAO Workflow

For populating the Decision Framework [44] as discussed in Section 4.8, we need to collect all of the elements of information. The research objective is to determine how/where to collect all of the information reflected Figure 35 from rigorously specified models. Based on inputs from Dr. Matt Cilli, some of the underlying computations are going to be published in a journal paper. This would allow us

to perform most of the computation directly on the data stored in a triple store, and then extract information directly for the visualization. Matt is using this approach with the research affiliated with the Engineered Resilient Systems effort and created the visualization using Tableau software. This would provide senior leaders and program managers the type of information they need to consider technology capability tradeoff using Performance, Cost (Affordability), Time (delivery schedule) and Risk, as shown in Figure 34.

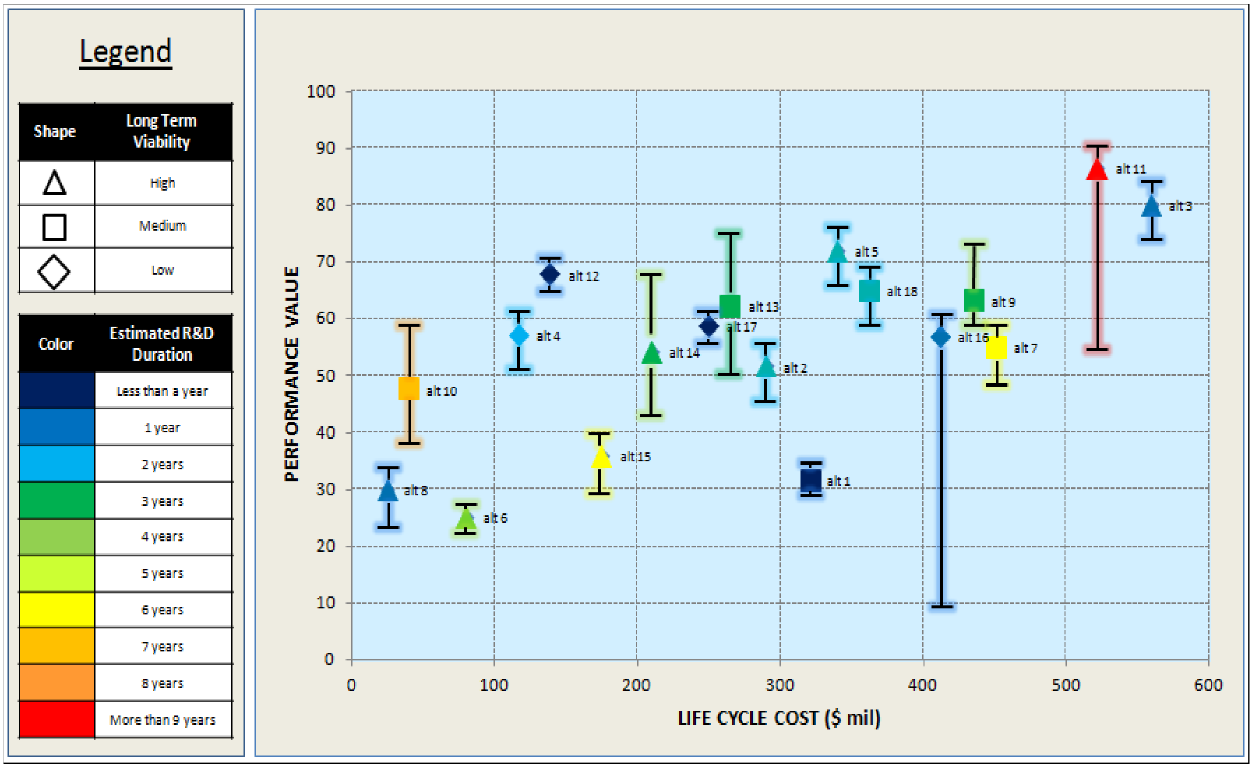


Figure 34. Visualizing Alternatives – Value Scatterplot with Assessing Impact of Uncertainty

Fundamentally, if a particular answer was unacceptable, using the concept discussed herein, we could trace linkages through the Information model back to all other related perspectives on the system in terms of operational, mission, system, and subsystem design alternatives and trades. These elements would include:

- Objective hierarchies
- Value functions
- Assessment Flow Diagrams (AFDs) trace the relationships between physical means, intermediate measures, and fundamental objectives
- Uncertainties

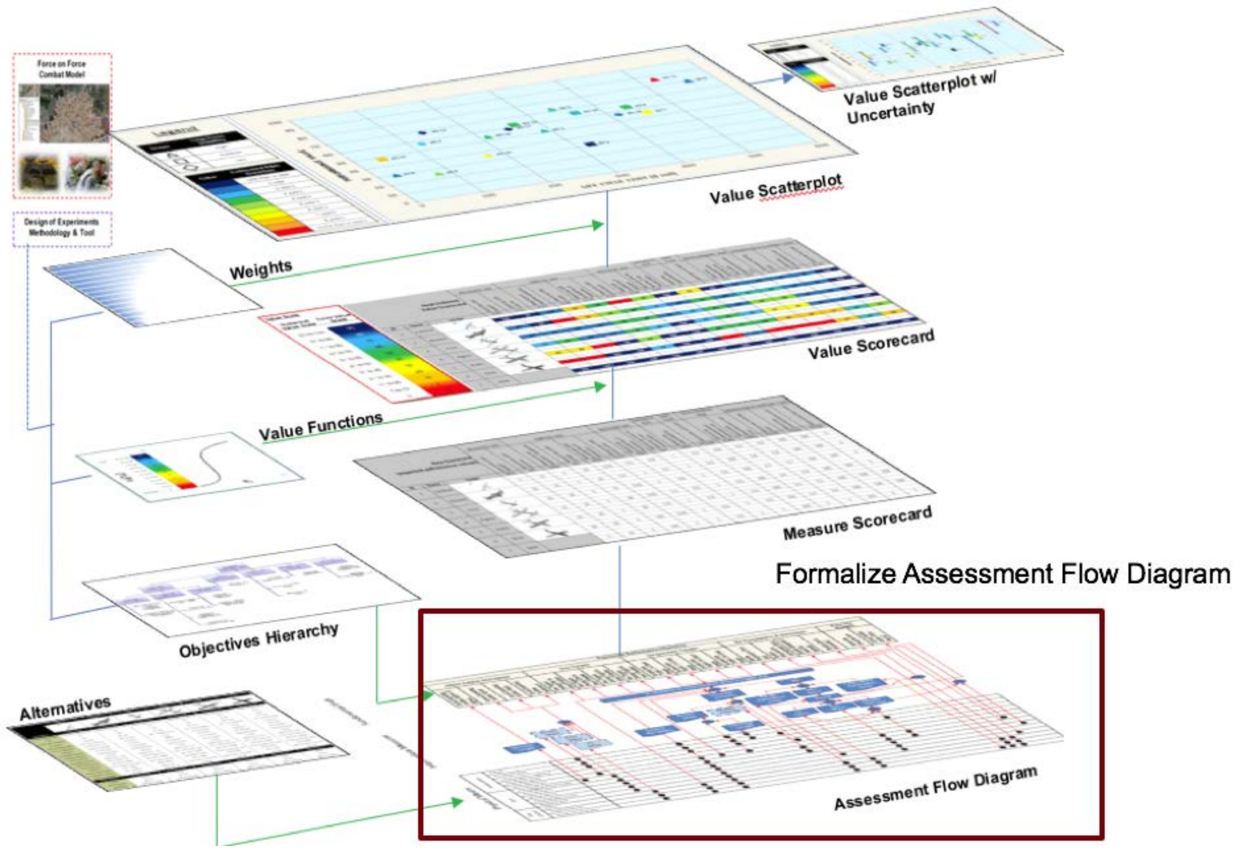


Figure 35. Decision Support Model Construct

This research used a case study documented in Matt Cilli's book chapter. We focused on formalizing the AFD using SysML, which is usually done in PowerPoint, as shown in Figure 36. This research investigates if we can formalize the AFD in SysML and be transformed into an MDAO workflow. Similar to the approach discussed in Section 5.6, we started with SysML and used the MBSEPak to produce the MDAO workflow, as reflected in Figure 36, which provides a basic conceptualization for researching this concept and to address the questions:

- Can MDAO represent Assessment Flow Diagram?
- Does AFD characterize needed MDAO workflows?

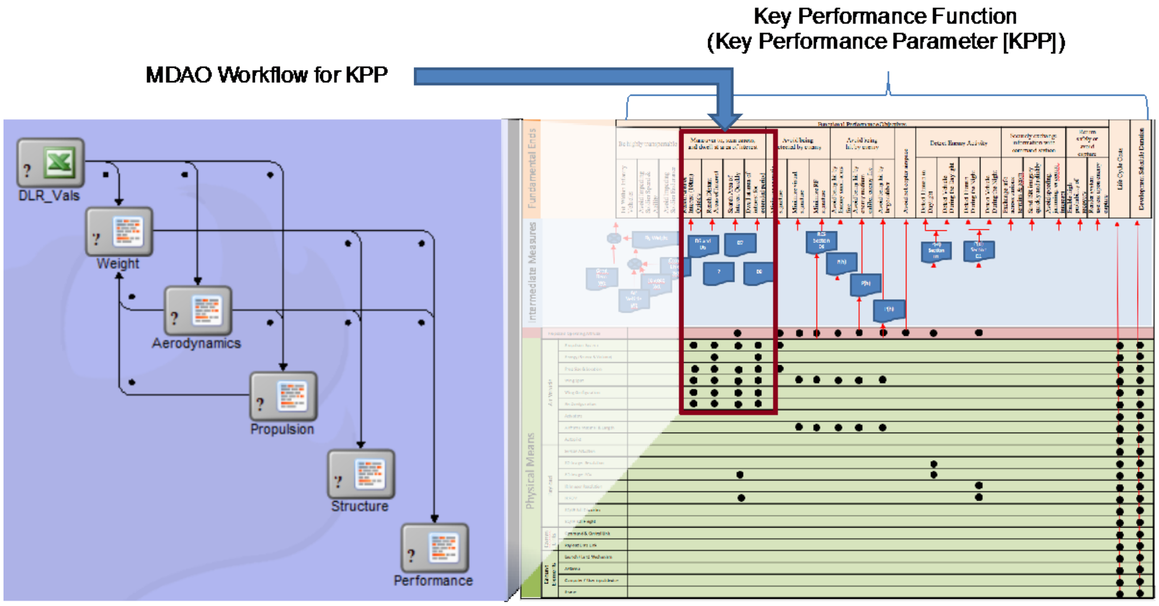


Figure 36. Formalizing the Assessment Flow Diagram

The current results have formalized the representations of AFD using SysML, MBSEPak and ModelCenter, because the Key Performance Parameters can be mapped to one or more MDAO workflows as reflected in Figure 36. With some recommendation on modeling best practices for using MBSEPak with SysML from Phoenix Integration. A Webinar explaining this approach is provided at the Phoenix Integration website (https://www.phoenix-int.com/learn-more/webinars/) called "Applications for Three Research Use Cases in Model Centric Engineering using ModelCenter and MBSEPak." [21]

The modeling steps follow from the Decision Support Construct:

1. Model system structure in SysML
2. Model as derived value types in SysML decomposition
3. Add the needed Measure scorecard that contains the Metrics of interest in the analysis
4. Value scorecard provides basis to compare metrics as perceived by user

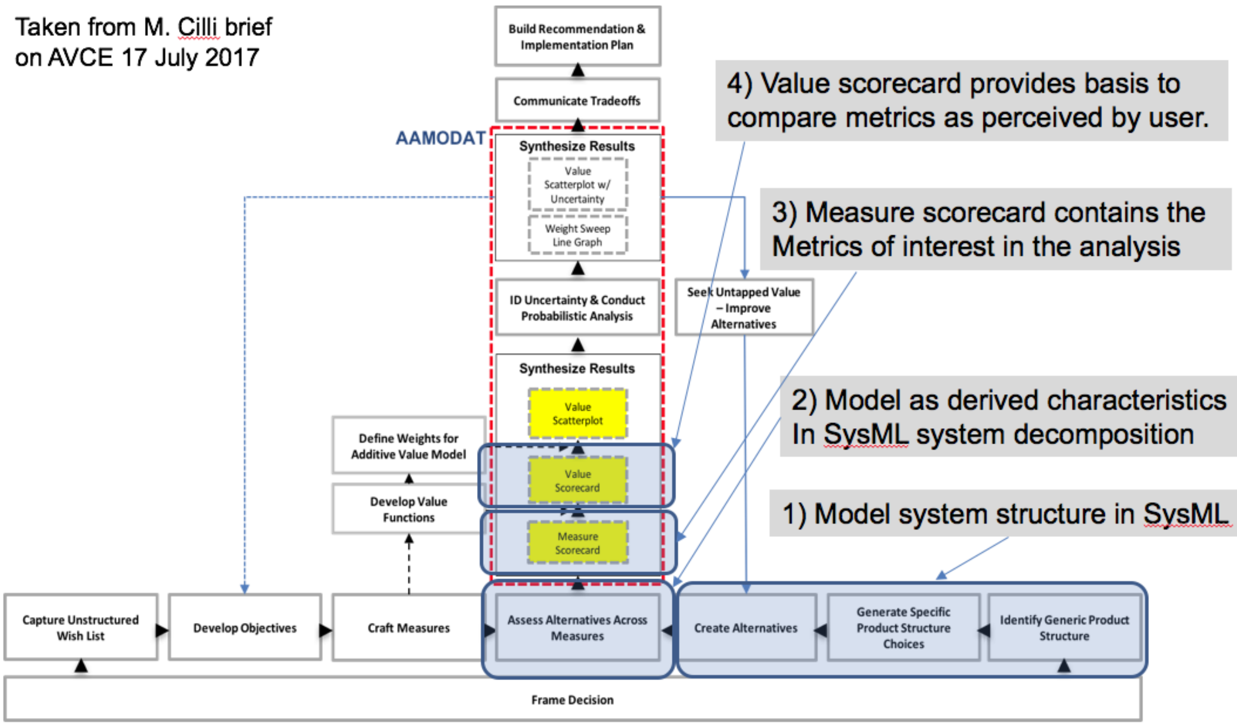


Figure 37. Decision Support Model Construct

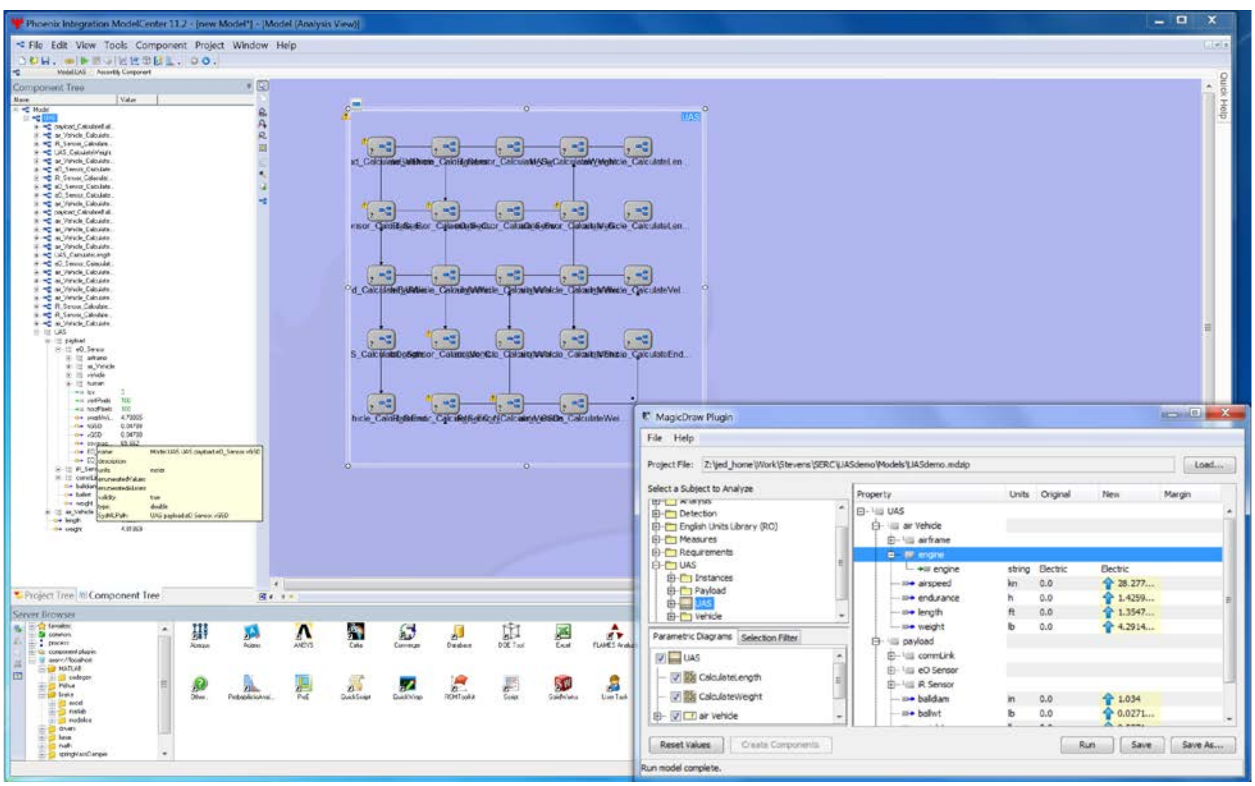


Figure 38. MBSEPak Creates Analysis Workflow and Checks Data Type Consistency

6 UC02: Integrated Modeling Environment (IME)

This use case investigates topics for Integrated Modeling Environments (IMEs) with specific focus on creating and collaborating in an Authoritative Source of Truth (AST) for the surrogate pilot in the context of the research thrusts. This includes, but is not limited to:

- Formalization of the collaboration using an AST, in the context of NAVAIR, but also in the context of one or more industry contractors
- Model visualization from multiple perspectives including, but not limited to enabling different views relevant to different stakeholder (or due to particular access), reducing complexity, and analytical analysis
- Methods for model modularization to ensure separation of concerns, classification, and acquisition
- Methods for creating and organizing Enterprise, Process, and Reference models
- Understanding the operational paradigm between industry and government in the context of the SET Framework through MCE
- Workflow analysis and representation relative to a program instantiation of tool suites from the IME
- NOTE: cyber security and classification is not currently in the scope of this work

6.1 Canonical Reference Architecture for Integrated Modeling Environment

Our prior research suggested that the following types of capabilities characterized as a canonical reference architecture of an Integrated MCE Environment represent the aggregate of what is in use by different organizations across industry and government [9] [10] [11] [43] [57] [75] [80] [118] [86] [127], as shown in Figure 39. The following provides some perspectives on these general capabilities:

- Provides appropriate views for the various stakeholders
- Stakeholders have views into the Single Source of Truth (SST)
  - We think that there can be a SST, but in the context of a broader ecosystem required for model-based acquisition, where the government and generally multiple contractors have their own environment that the notion of an Authoritative Source of Truth (AST) may be more appropriate
  - Using rich modeling interfaces for those with expertise in modeling
  - Using rich “web” interfaces, which today provides support for graphics, integrated with structure inputs, generated textual views and 3D model viewing [132]
- MDAO layer provides for problem and design space exploration of
  - Physics-based models
  - Integrity-based models
  - Cost and scheduling models
  - Risk models
  - Various “illities” models
- Includes surrogates and components
- Enabled by High Performance Computing (HPC)
- Semantically rich linkages between data and information in the AST provides for continuous workflow orchestration between government and contractor(s) – enabled by more HPC
- Document generation is enabled by
  - Semantically rich links to information in the AST

- Templates that formalize patterns for requirements, contracts, etc.
- Enabling technologies such as machine learning provides a virtual knowledge librarian that assist users guided by embedding knowledge and training
- Contractor and collaborators have a secure means to plugin to view or share digital information, as a new paradigm for interactions
- This view of the Designing System provides links downstream to fully link Product Lifecycle Management (PLM)

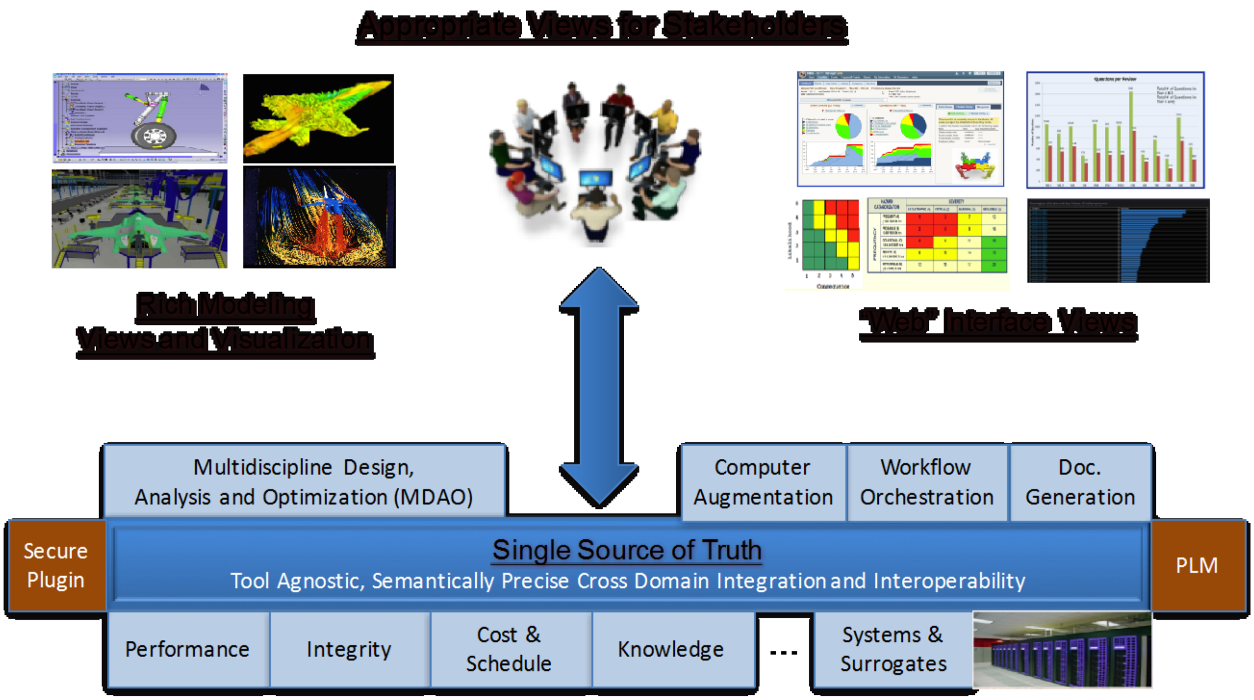


Figure 39. Integrated Environment for Iterative Tradespace Analysis of Problem and Design Space

We also believe that in the context of the SET Framework, these capabilities may be distributed between government and industry coupled by the AST. Our surrogate pilot will hopefully provide additional insight into those beliefs.

6.2 Integrated Modeling Environment for Surrogate Pilot

Given the context about IMEs, we have been able to assemble some relevant tools in the Stevens laboratory, but also deployed an instantiation of OpenMBEE to an Amazon Web Service server to support the surrogate pilot, which notionally will contain elements shown in Figure 22. We anticipate the surrogate contractor to have some of the same tools (e.g., MagicDraw), but additional tools that they have developed for MDAO, model-based design and collaboration. The objective will be to define the operational paradigm by which we look at these linked pieces of model elements (from the SET Framework) into an AST. The OpenMBEE is now operational can be quickly installed using Docker [62]. The current research thrusts are to integrate one or more environments to establish a distributed AST. We also need to define and characterize the needed capabilities of IoIF, given that we will leverage tool-to-tool integration (e.g., Magic Draw and ModelCenter). We believe that these capabilities may be similar to those discussed as RangeDB in the context of the Airbus environment shown in Figure 18.

The IoIF provides a framework to effectively interchange information using SWT and data acquisition functionality as shown in an example in Figure 40. This framework is being designed to be used with various software tools and various simulation environments. Each tool or simulation would have a Proxy to perform Publish (send information) and Subscribe (receive information) functions. The DAA layer would also interact with SWT of integrated ontologies to computationally interrelate and transform information such as the example discussed in Section 4.5. The immediate goals are:

- Abstracts away from the software client tools as much knowledge and dependencies of the tool-to-tool data integration architecture as possible
- Allows for tool-to-tool data integration on computer systems that are physically remote from each other
- Uses an ontology framework (i.e., SWT) that implements an automated decision process regarding tool/data relationships
- Uses a Publish / Subscribe framework that implements an automated data transport layer between various software client tools
- Investigate how to integrate with OpenMBEE

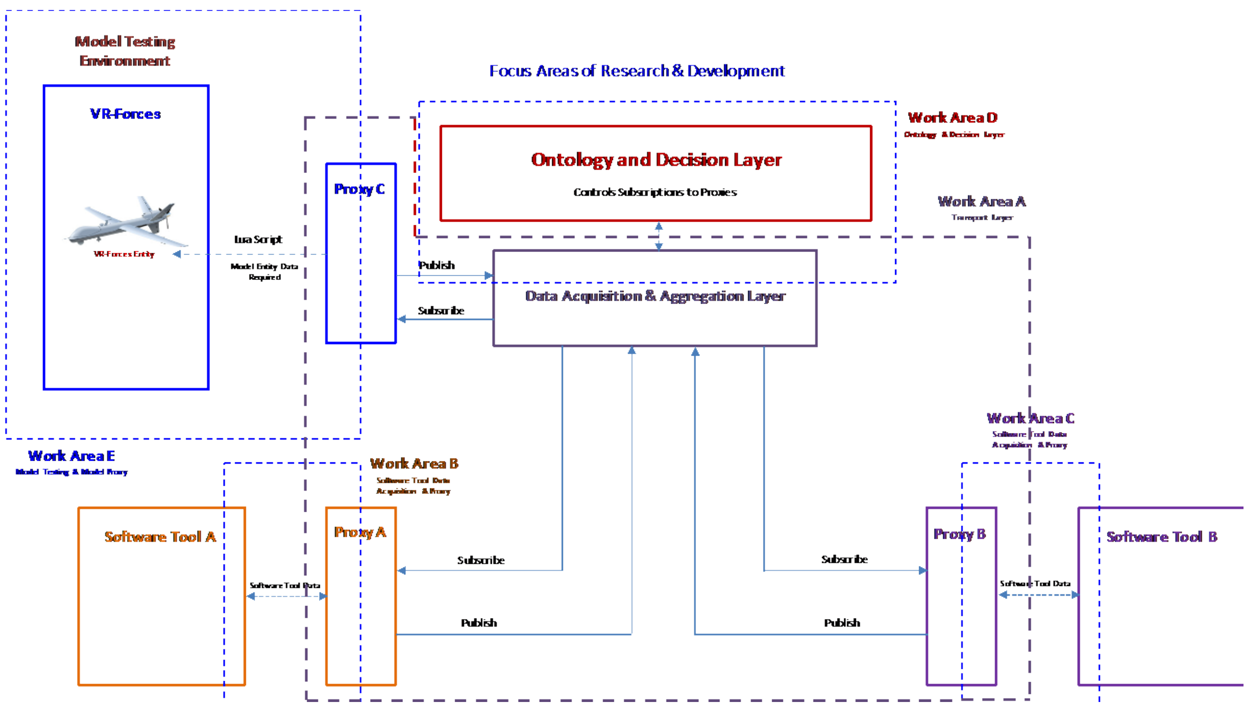


Figure 40. Tool-to-Tool Integration and Interoperability Framework

7 UC03: Modeling Methods

This use case investigates the development and demonstrations of methods for technologies in the context of the IME workflows, such as:

- Methods for mission model
- Methods for system model
- Methods for modularizing models to support constraints needed for developing an authoritative source of truth, which relates to many other use cases
- Methods for model management

- Methods for representing and organizing reference models, process models, discipline-specific models
- Methods for MDAO modeling are discussed in Section 5
- Methods for traceability
- Alternative approaches to improve modeling methods, which is fundamental to ensuring model integrity

7.1 Mission Model

The approach for developing the mission model is based on an Integrated Capability Framework (ICF) Operational Concept Document (Version 3.2) 22 February 2016. This document is considered "Distribution D," which means it may only be available to companies that are doing business with the government. However, the Skyzer Mission model will be made available publically on the Amazon Web Services server. This approach demonstrates that modeling can be used and comply with existing standards that traditionally have been document-based.

The guidelines include:

- Thoroughly define required mission capabilities, measures of effectiveness, and associated operational conditions and constraints.
- Identify System of Systems (SoS) interfaces and measures of performance through structured decomposition of required mission capabilities.
- Provide a common, cross-Systems Command (SYSCOM)/Program Executive Office (PEO) framework to facilitate enterprise level engineering across the SYSCOMs and enable efficient system integration and effective force interoperability.
- Establish enterprise data structures and implementation guidance to enable iterative development of enterprise architectures
- The consistent implementation of ICF practices and guidance across assessments and stakeholders supports:
  - A common understanding of mission requirements and a structured process to identify and align systems and platforms capabilities to support missions.
  - System and platform owners with a thorough set of interoperability requirements and knowledge of what platforms, interfaces and behavior to which they need to design, along with associated standards.

We have a View and Viewpoint hierarchy that extracts information from the Skyzer Mission model to "generate a specification," which aligns with the guidelines of the ICF. A portion of the View and Viewpoint hierarchy is shown in Figure 41.

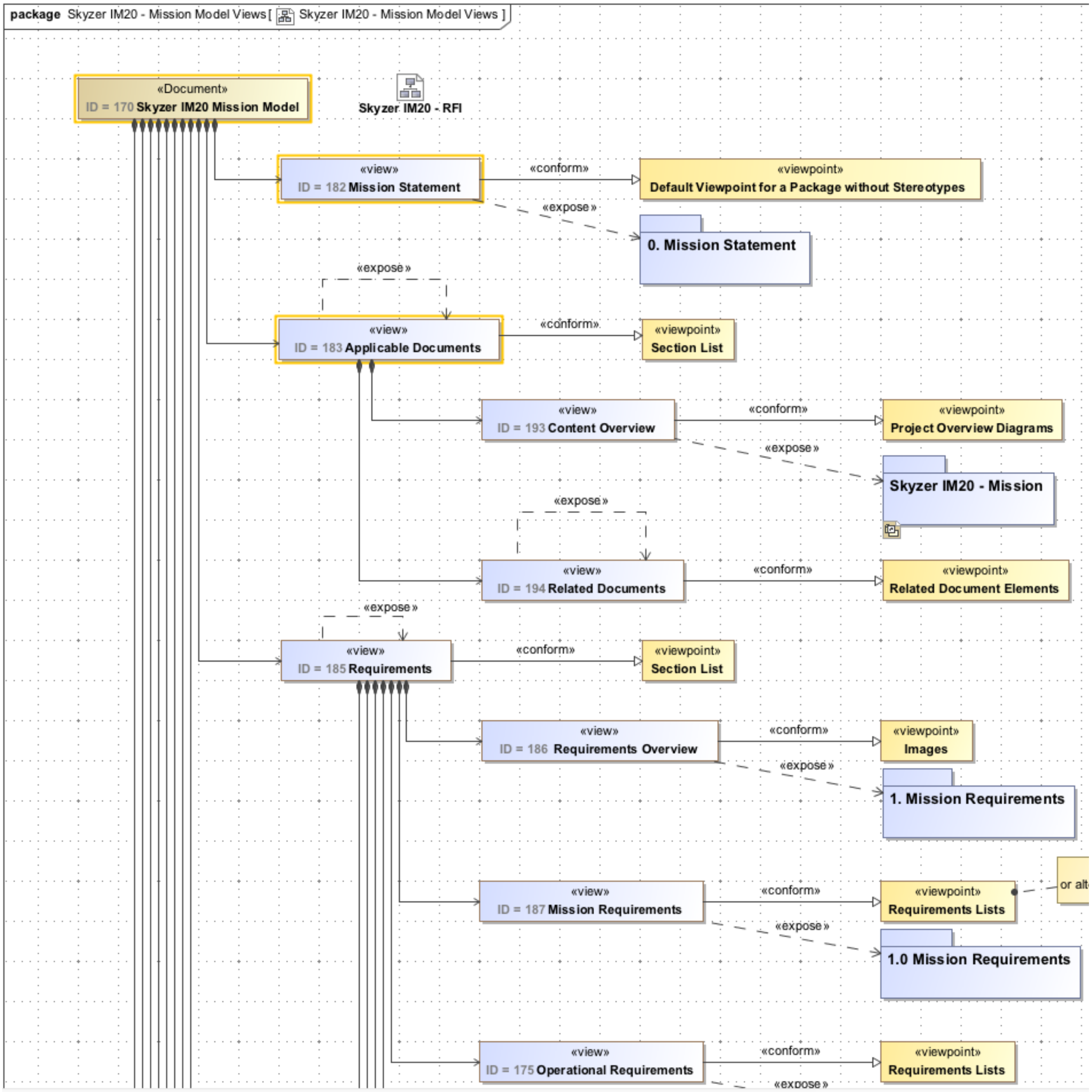


Figure 41. View and Viewpoint Hierarchy for Surrogate Pilot Mission Model

7.2 System Model

NAVAIR decided to adopt Object-Oriented Systems Engineering Method (OOSEM) [98] as the default for System Modeling using SysML. There are many resources available that describe OOSEM. The main activities have been captured as a reference model. An example of is shown in Figure 42.

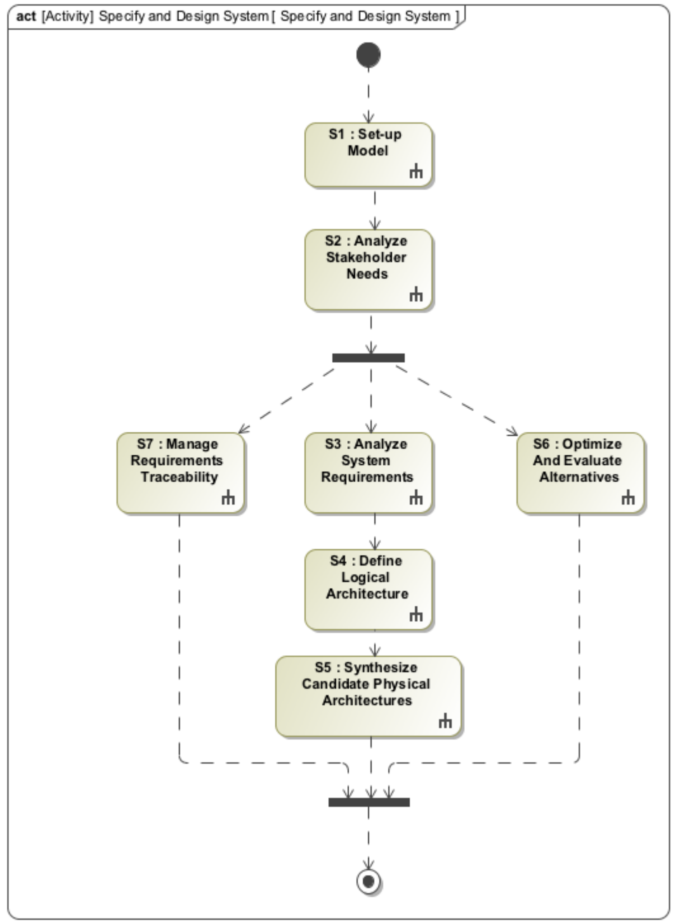


Figure 42. OOSEM Top Level Activities

7.3 MODULARIZING THE SYSML MODEL

The method for modularization models is also an important part of our surrogate pilot effort. As shown in Figure 43, we are using an approach for modularizing the surrogate pilot model that uses a "model reference" (Project uses) concept so that the mission, system and other models can be created independently, but could be referenced in an overarching project/program model. For example, in the containment tree on the left side of Figure 43, there are some packages, (e.g., Enterprise, Reference Models) that are in normal black font, but two models the Mission Level and System Level are slightly "grayed out," because these projects are references to separate models. In doing this, we can allow the Mission model and System model to be worked on separately, but when brought into the higher-level project model, we could view the entire model. In addition, as shown in the View and Viewpoint hierarchy, we can include these referenced models in one or more Views with Viewpoints, where DocGen can then generate a document or specification for the entire project or a subset of elements from various models. This concept of modularization would apply to other process models, such as those developed by competencies and reference models. We are investigating this evolving method, because it plays heavily with model management including tradeoff for both the Teamwork Cloud and OpenMBEE MMS.

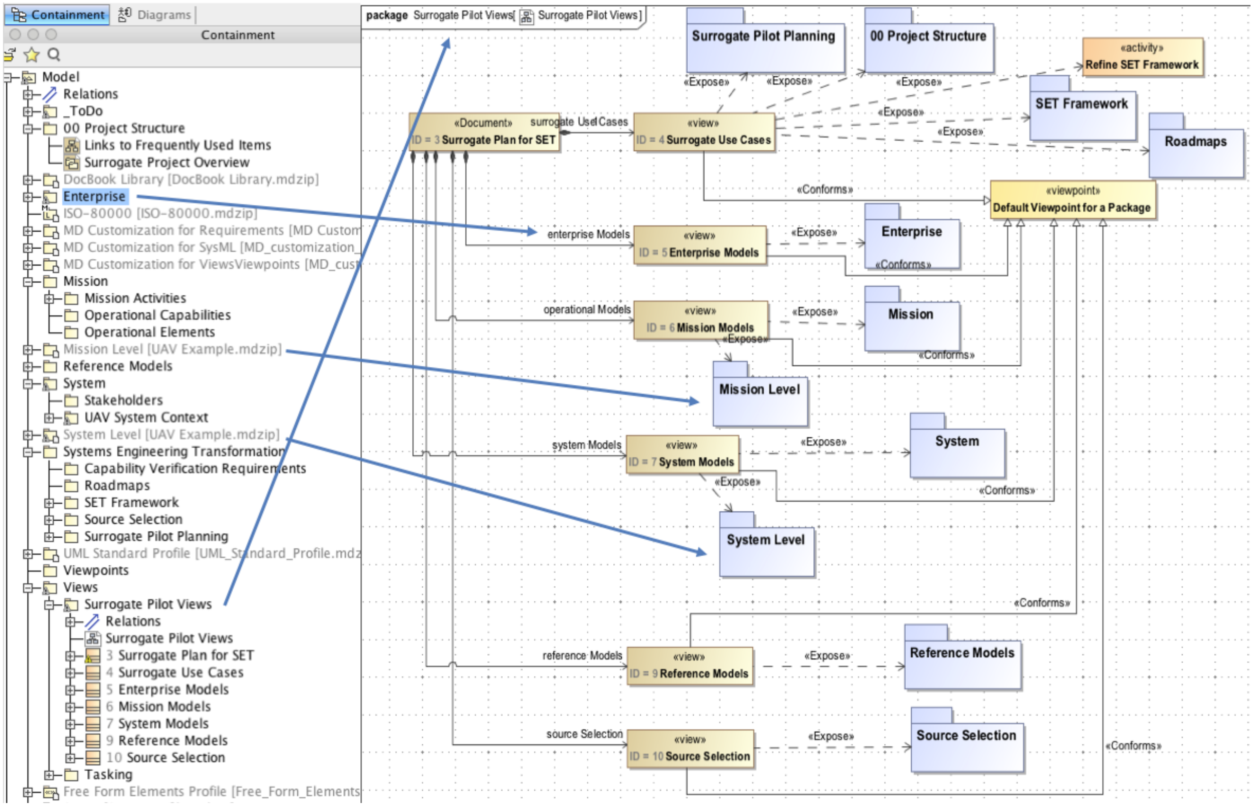


Figure 43. Modularizing Surrogate Pilot Model

7.4 Views and Viewpoints

The basic elements, as shown in Figure 44 can be included within an overarching document, which includes:

- Document – the overarching model element
  - Document can include other documents, which also provides another level of modularization and support for reuse
- View (there can be one or more views in a document)
- A View uses the Exposes relationship to associate the View with some element in the model (e.g., Package, Diagram, etc.)
- View conforms to a Viewpoint
- Viewpoint in Model Development Kit (MDK) is a special language created out of a profiled activity diagram that can collect, filter, and then produce a document through a DocBook standard

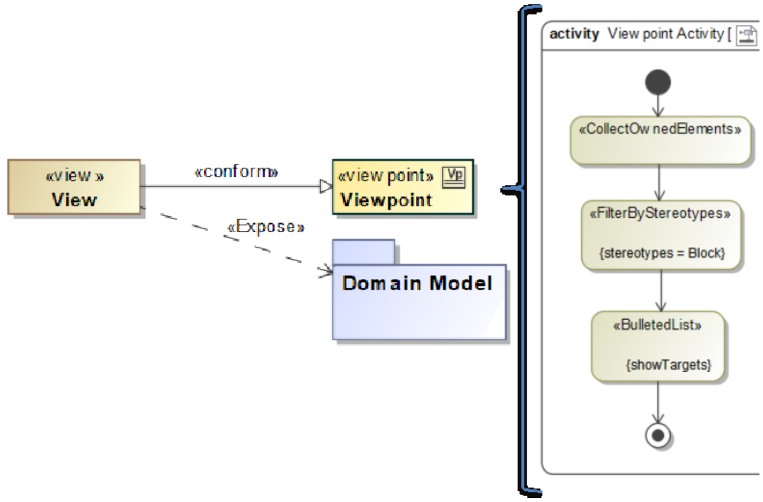


Figure 44. Element of View and Viewpoints

A document assembled from a number of Documents or Views can be generated into DocBook, which can then be generated into PDF, Word, HTML, and other formats. However, these Views can also be "pushed" into the OpenMBEE Model Management System (MMS) as shown in Figure 45. The View Editor can then be used to view the generated specification; in addition, it can export (generate) into Word, PDF, and HTML. The View Editor also allows for editing and updating a generated view that can also be pushed back into the MMS, as well as back into the model (for certain types of model elements).

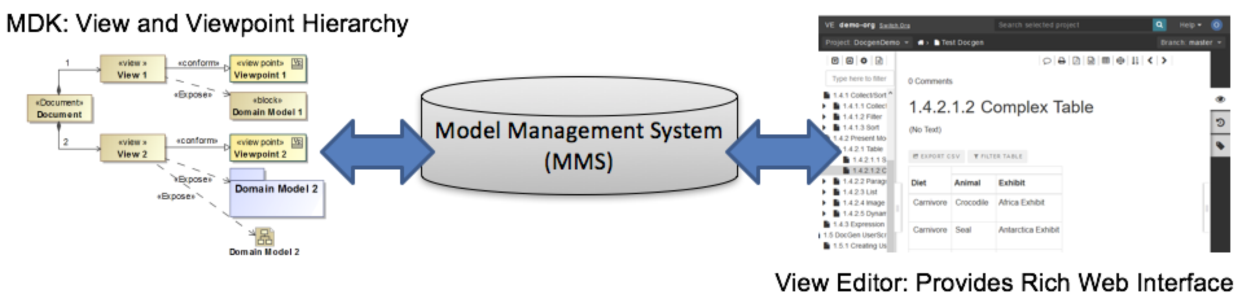


Figure 45. Views are Pushed into Model Management System and Viewable through View Editor

As shown in Figure 46, the View Editor runs in a standard browser and lets users navigate the View hierarchy, and visualize specific Views within the hierarchy, edit the views and examine history associated with changes of the View. There are capabilities for branching those changes. This is part of the future research to investigate the combination of facets related to View and Viewpoint hierarchies, model management in MMS as well as in Teamwork cloud. We are expecting some support from NASA/JPL who is developing some type of guideline, and working in conjunction with our NAVAIR sponsors on the best methods for model management.

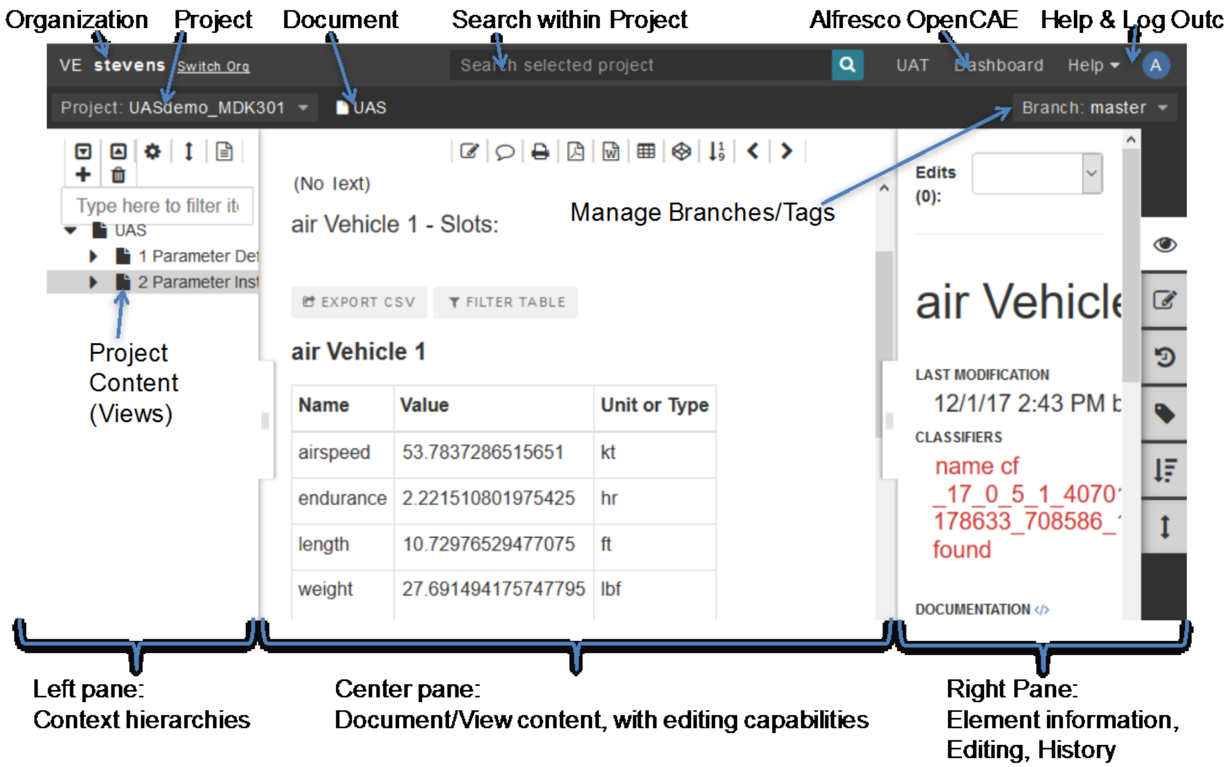


Figure 46. View Editor

7.5 METHODS FOR TRACEABILITY

SysML and most of the modeling tools provide means for capturing traceability information, including various standard stereotypes. Our concern is tracing between the model levels, from mission to system to design models, and linking back to the KPPs. This is yet another objective that is defined in the surrogate project plan, but we have not gotten deeply enough into the modeling to characterize how best to support linking models at different levels. This is part of the research to be continued under the new RT-195 research task.

8 UC04: MODEL-PHYSICS MODELING AND MODEL INTEGRITY

This use case investigates model-physics modeling, MDAO and model integrity which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty. Model integrity, from our sponsor's perspective, is a means to understand margins and uncertainty in what models and associated simulations "predict" or in other words when/how do we trust the models. The objectives characterized by the sponsor are to ensure that the research covers the key objectives, which included:

- Include both models to assess "performance" and models for assessing "integrity" such as:
  - Performance: aero, propulsion, sensors, etc.
  - Integrity: Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), reliability, etc. – can we build it, can we trust it
  - A stated challenge was: how can "integrity" be accomplished when the current situation involves federations of models that are not integrated?

- Continuous hierarchical and vertical flow enabled by models and iterative refinement through tradespace analysis, concept engineering, and architecture and design analysis

8.1 Surrogate Pilot Design Model Constraint

We have imposed constraints on the mission scenarios for the surrogate pilot to ensure that we have the opportunity to evaluate multi-physic designs and measures for understanding model integrity to support a production readiness decision. During Elements 1 and 2, we would use MDAO type analysis such as described in Section 5.4. The more critical aspects that concern our sponsor are the ability to deal with designs in Element 3, that can support a producability decision associated with Element 4 when multi-physics design elements are involved in the decision process; that is, can we make a production decision from various type of modeling and simulation analyses of a design. An example is shown in Figure 31, which shows that there can be significant differences in the system design tradespace when both CFD and FEA are used in the same MDAO workflow. Therefore, this is another key objective of the surrogate pilot. The objective is to define mission use cases that can be used to force analysis to better understand the feasible multi-physics design options.

8.2 Advanced Approaches to Model Integrity

It is currently unclear if NAVAIR, in the context of the SET Framework, will ever deal with multi-physics consideration during Element 1 and 2 of the framework. Most of the analysis will likely be parametric in nature during Element 1 and 2. However, we do know that Sandia National Laboratory has discussed some of the most advanced approaches for supporting uncertainty quantification (UQ) to enable risk-informed decision-making [111]. Their methods and tooling address the subjects of margins, sensitivities, and uncertainties. The information they provided reflects on the advanced nature of their efforts and continuous evolution through modeling and simulations capabilities that operate on some of the most powerful high-performance computing (HPC) resources in the world. We heard about their HPC capabilities, methodologies on Quantification of Margins and Uncertainty (QMU), an enabling framework called Design Analysis Kit for Optimization and Terascale Applications (DAKOTA) Toolkit [141], and the need and challenge of Model Validation and Simulation Qualification [138]. They also discussed the movement towards Common Engineering Environment that makes these capabilities pervasively available to their entire engineering team (i.e., the designing system in our terminology). We think their capabilities provide substantial evidence for the types of capabilities that should be part of the risk framework. This section provides additional details.

Traditional approaches referred to as Verification, Validation and Accreditation (VV&A) of modeling and simulation capabilities are still relevant and used by organizations. VV&A, in principle, is a process for reducing risk; in that sense VV&A provides a way for establishing whether a particular modeling and simulation and its input data are suitable and credible for a particular use [61]. The words “tool qualification” [63] and “simulation qualification” [138] have also been used by organizations regarding the trust in models and simulations capabilities. A more extension discussion of this subject is provided in RT-141 [28] and RT-157 [29].

9 UC05: Representation to formalize Monterey Phoenix for requirement verification and validation

This use case investigates the development of SysML representations to formalize the Monterey Phoenix (MP) research under RT-176 to support requirement verification and validation [70]. MCE does

provide some unique opportunity to be more effective at contributing V&V evidence in early design. Rigorously defined models can directly support V&V, and this could both subsume cost and risks.

The results accomplished against this effort to use SERC RT-176 effort of Monterey Phoenix for V&V of requirements is showing progress. The basic concept is to formalize using SysML graphics, and in this case activity diagrams and then transform into the MP language as shown in Figure 47. MP then uses the formal language to generate graphical representations of the behaviors, as shown in Figure 48 [133] that can be derived from the language of the formalized behavior to a given scope level (e.g., Scope 2 in Figure 47). The verification step does require a person to check the different behavioral representations for correctness. This concept is similar to model checking.

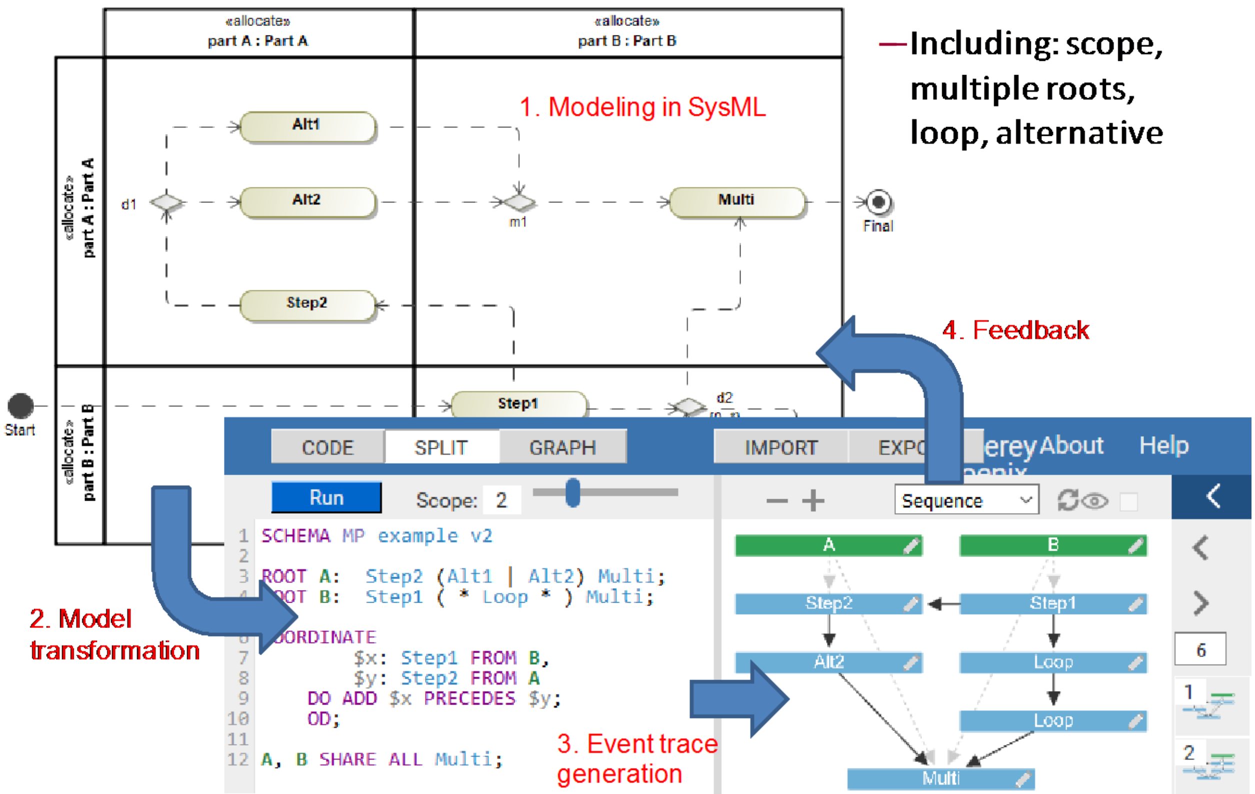


Figure 47. Representation and Transformation from SysML Activity Diagrams to MP

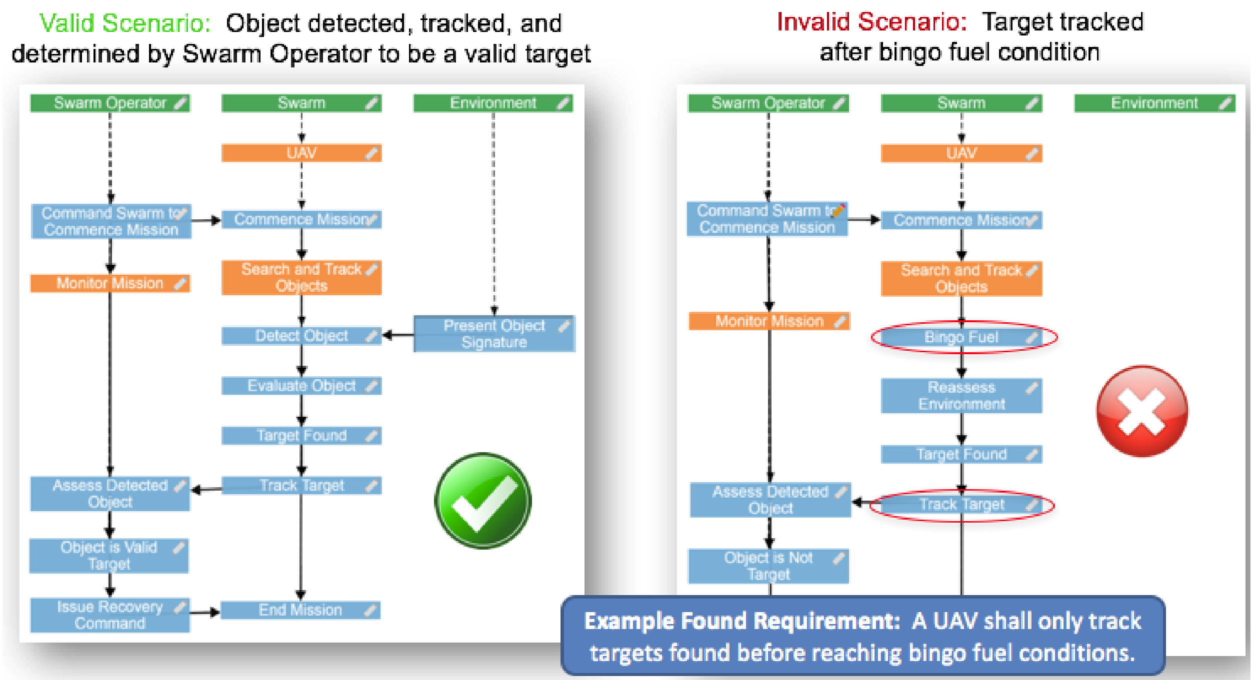


Figure 48. Generated Visualization of Scenarios by Monterey Phoenix

More information on Monterey Phoenix can be found:

- MP Public Website: wiki.nps.edu/display/MP/
- MP Analyzer on Firebird: http://firebird.nps.edu
- Giammarco, K., *Practical modeling concepts for engineering emergence in systems of systems*, in *12th System of Systems Engineering Conference (SoSE)*. 2017, IEEE. p. 1-6.
- Revill, M.B., *UAV swarm behavior modeling for early exposure of failure modes*. 2016, Naval Postgraduate School: Monterey, CA.
- (pending) Quartuccio, J. and K. Giammarco, *A Model-Based Approach to Investigate Emergent Behaviors in Systems of Systems*, in *Engineering Emergence: A Modeling and Simulation Approach*, L. Rainey and M. Jamshidi, Editors. 2017.

10 UC06: EXPERIMENTATION AND LEARNING FOR RESEARCH TOPICS IN THE EXECUTION OF SET

This use case defines the objectives for experimentation and learning in the execution of the SET. This section is already characterized in an evolving state in the automatically generated report from the Surrogate Pilot Project Model, which effectively address the uses cases shown in Figure 49, and are being characterized in Section 3.4.

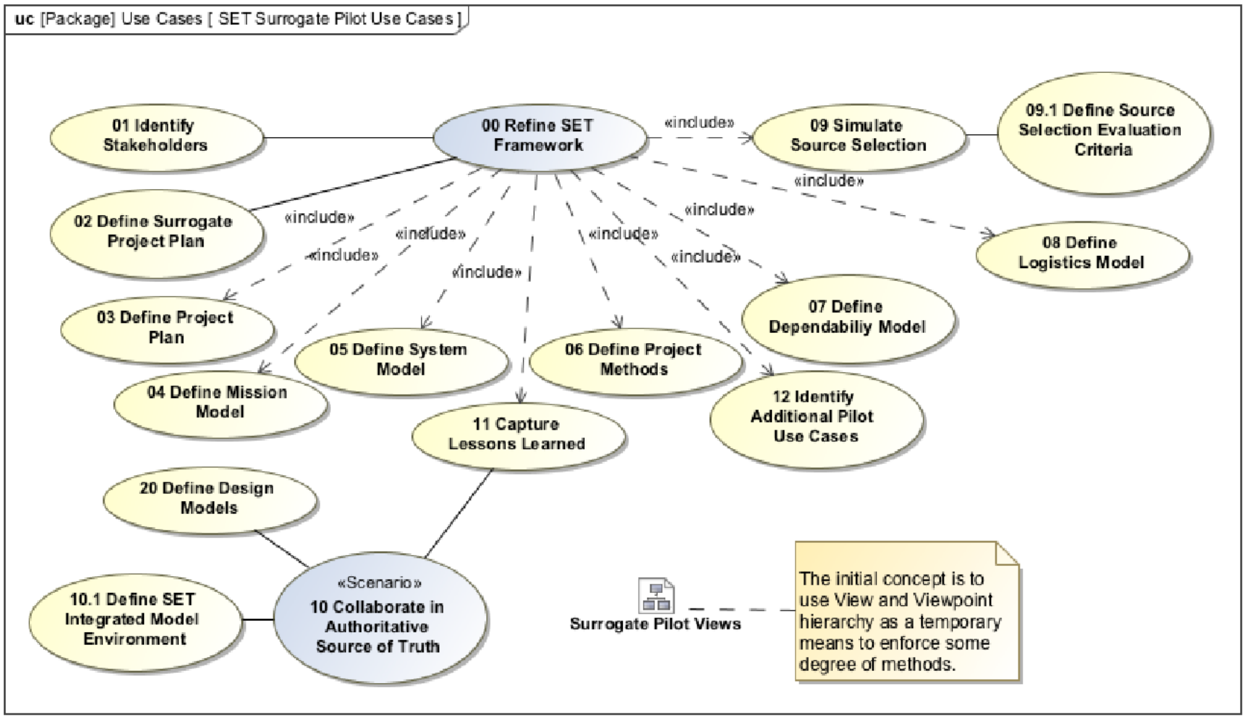


Figure 49. Identify Experimental Objectives for Use Cases

11 ENTERPRISE TRANSFORMATION TO SUPPORT GOVERNANCE AND WORKFORCE DEVELOPMENT

This use case is for research into Enterprise Transformation to support governance and workforce development. This has not yet been funded, but will be if RT-195 is funded. This research will be supported by Dr. Donna Rhodes from Massachusetts Institute of Technology.

12 SERC RESEARCH SYNERGIES

This section discusses some synergies to the ongoing NAVAIR research tasks that are briefly mentioned in this report to inform readers of the relationships to these other activities.

12.1 RT-168 ARDEC RESEARCH

The most significant research synergies are coming from the ARDEC research under RT-168. We do many types of event, meetings, demonstrations and discussions with ARDEC that include NAVAIR. We are using a Model Based System Engineering (MBSE) approach to model aspects of our project. We elaborate the research tasks using high-level use cases, relating those use cases, and associating the use cases with stakeholders involved in the research as shown in Figure 50. It should be clear that the use cases are related, and stakeholders (including some from ARDEC) are involved in multiple use cases. For example, both ARDEC and NAVAIR are interested in OpenMBEE. This bi-monthly status will be given primarily in the context of each use case, and not necessarily in terms of stakeholder contributions, because some efforts have several contributors.

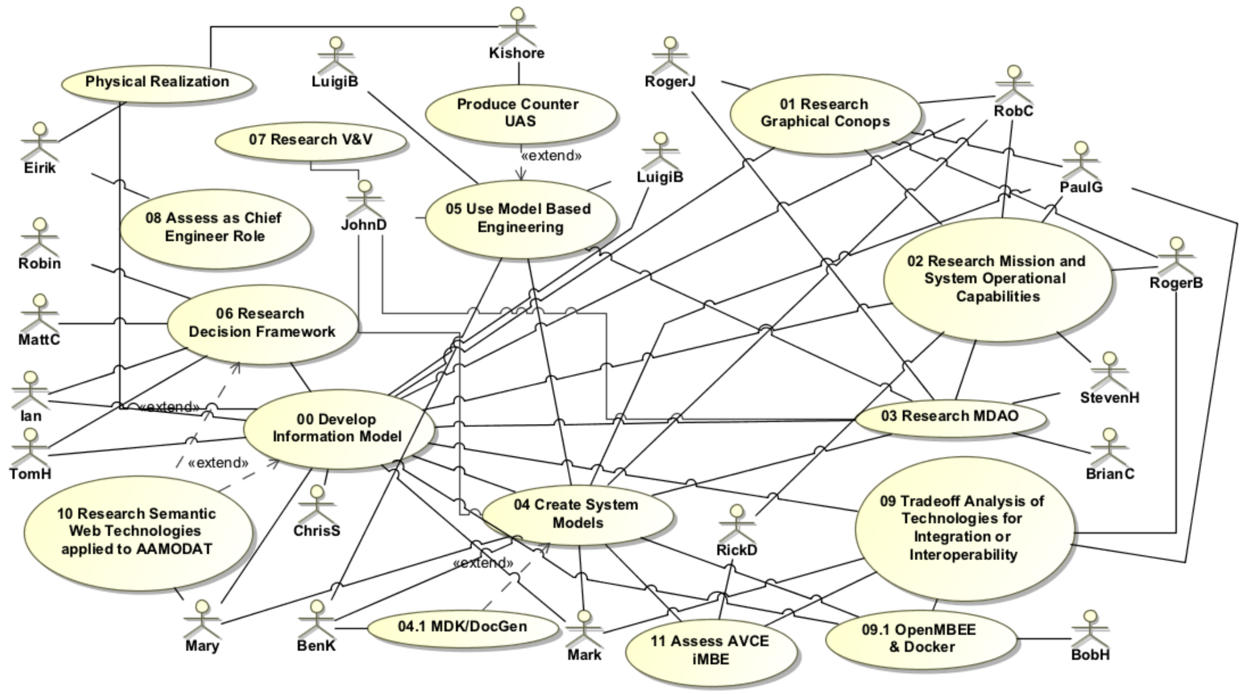


Figure 50. High-level Research Use Cases

12.2 RT-176 Verification and Validation (V&V) of System Behavior Specifications

Our NAVAIR sponsor had requested that the SERC RT-176 research task being led by Dr. Kristin Giammarco be aligned with the ongoing research from RT-157 and RT-170. This research synergy is discussed in Section 9.

12.3 Aerospace Industry Association CONOPS for MBSE Collaboration

This is a follow-up to the effort completed last year which developed a white paper on the Life Cycle Benefits of Collaborative MBSE Use for Early Requirements Development [3]. This white paper discusses the current state and benefits of MBSE across the entire life cycle and provides proposals for addressing such issues as MBSE Collaborative Framework, Government Data Rights, Intellectual Property, and Life Cycle Effectiveness with MBSE.

The effort for this year involves many of the industry contractors to NAVAIR and DoD. The results should produce a white paper describing a CONOPS for how industry and government can collaborate through MCE/MBSE.

12.4 OpenMBEE and Open Collaboration Group for MBSE

We recently joined the Open Collaboration Group for MBSE that is providing support for adopting and contributing to OpenMBEE [118]. We are planning to use OpenMBEE in our lab, and contribute to the community effort in order to advance it with capabilities developed under RT-168, RT-170 and RT-176. We have been invited to present our work on OpenMBEE and its relationship to the Surrogate Pilot to this group in April 2018.

12.5 SEMANTIC TECHNOLOGIES FOUNDATION INITIATIVE FOR SYSTEMS ENGINEERING

The NASA/JPL Symposium and Workshop on MBSE had a keynote talk given by Steve Jenkins that was fundamentally based on SWT and a foundational ontology for Systems Engineering developed my NASA/JPL. There were also two breakout sessions on the subject SWT. There was significant attendance at the break out session titled: "Ontologies, Formalisms, & Reasoning" possibly due to the motivation given by Steve Jenkins. In general, there is progress being made in this area and there is significant interest. Dinesh Verma has initiated an effort with the support of Chi Lin, Steve Jenkins and Mark Blackburn to bring a community of people together in an attempt to create and ecosystem on Semantic Technologies for Systems Engineering.

The working group has created a charter and mission:

- Charter
  - The Semantic Technologies Foundation Initiative for Systems Engineering is to promote and champion the development and utilization of ontologies and semantic technologies to support system engineering practice, education, and research.
- Mission
  - The mission of the initiative is to collect a suite of interoperable ontologies that are logically well-formed and accurate from both scientific and engineering points of view. The initiative will charter a collective of stakeholders that are committed to collaboration and adherence to shared semantic principles for the advancement of systems engineering. To achieve this, initiative working group participants will voluntarily adhere to and contribute to the development of an evolving set of principles including open use, collaborative development, and non-overlapping and appropriately-scoped content. They will capture and maintain metadata for each ontology to encourage implementation and reuse.

12.6 NATIONAL DEFENSE INDUSTRY ASSOCIATION MODELING AND SIMULATION

National Defense Industry Association (NDIA) Modeling and Simulation group is looking at approaches for using digital engineering for competitive down select. We are involved in all of these efforts to further the objectives of our sponsor in August of 2016.

At the request of David Allsop from Boeing, we also connected a few people from our NAVAIR visits to discuss the issue of deriving MDAO parametrics from high-fidelity models, or more generally having some type of bi-directionality between parametric models and higher fidelity simulations (which can "break" the parametric chains). Dr. Dave McCormick who runs the MDAO lab for Northrop Grumman gave a relevant presentation at the April National Defense Industrial Association (NDIA) Modeling and Simulation bi-monthly committee meeting on some of challenges, which we believe are relevant to future research, such as:

- Rapid re-parameterization of completely new concepts
- Ability to incorporate static models
- Ability to bring in static changes "underneath" the parameterization
- Ability to incrementally add to parameterization
- Ability to rapidly alter the sizing logic behind models

13 PART II SUMMARY

This report has presented overviews of our SERC research to contribute to the NAVAIR Systems Engineering Transformation (SET). This report provides a high-level summary of the research-related events, results and deliverables. Our research from the early research tasks of RT-48/118/141 has transitioned from investigating the most holistic and advanced approaches to MCE and more generally Digital Engineering (DE) to demonstrate the art-of-the-possible in the context of the surrogate pilot experiments. The path forward to transitioning to DE presents challenges and opportunities, both technical and sociotechnical. The research has determined both industry and DoD are advancing pieces of the envisioned DE ecosystem and the technology is available to bring the DE ecosystem into existence, but there are still many research opportunities needed to fully realize the goals of a complete DE transformation. There are at least three key enablers: (1) Information Technology (IT) infrastructure, (2) workforce, and (3) policy to foster a new model for acquisition.

IT infrastructure broadly includes all of the underlying computational technologies that have helped the Internet change our lives. These include a well-designed and secure suite of computational technologies, such as modeling and simulation, and semantic technology. The technologies could enable completeness and consistency checks, as well as methodological guidance for the creation of digital information from all types of media throughout multiple tools in the system lifecycle. The formalization of this information as models, provides future opportunities to leverage technologies that allow for semantically-rich data exchange, semantic reconciliation, and reasoning about information that would promote enhanced communication across stakeholders and provide the ability for computer augmented SE decision support. The modeling infrastructure for our surrogate pilot environment is a key step to enable an AST. We have an operational environment based on OpenMBEE, commercial tools and some integration and interoperability technologies. We look to the follow-on research task of RT-195 to connect a government-side of the AST with industry surrogate contractors.

NAVAIR has made strides to advance the workforce through system modeling training. Our surrogate pilots are also providing demonstration and examples for mission and system modeling. The combination of basic training and examples created using best practices modeling methods, provides some initial steps toward understanding how different types of modeling artifacts can replace tradition document-based acquisition processes and artifacts. The surrogate pilot experiments to execute the SET Framework can provide a baseline for a next generation model-based acquisition paradigm. Acceptance of a DE ecosystem by the workforce can be another enabler to the DE transformation, and research suggests that education and training can make it successful. These demonstrations of the technology to the workforce should be enablers that reach more broadly throughout the DoD. Our interactions with other DoD stakeholders suggests that they too are ready to make the transformation in both policy and culture to enable the DE ecosystem.

14 ACRONYMS AND ABBREVIATION

This section provides a list of some of the terms used throughout the paper. The model lexicon should have all of these terms and many others.

AADL	Architecture Analysis & Design Language
ACAT	Acquisition Category
AFT	Architecture Framework Tool of NASA/JPL
AGI	Analytical Graphics, Inc.
AGM	Acquisition Guidance Model
ANSI	American National Standards Institute
AP233	Application Protocol 233
ATL	ATLAS Transformation Language
ASR	Alternative System Review
AST	Authoritative Source of Truth
AVSI	Aerospace Vehicle Systems Institute
BDD	SysML Block Definition Diagram
BN	Bayesian Network
BNF	Backus Naur Form
BOM	Bill of Material
BPML	Business Process Modeling Language
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CDR	Critical Design Review
CEO	Chief Executive Officer
CESUN	International Engineering Systems Symposium
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CORBA	Common Object Requesting Broker Architecture
CREATE	Computational Research and Engineering for Acquisition Tools and Environments
CWM	Common Warehouse Metamodel
dB	Decibel
DBMS	Database Management System
DAG	Defense Acquisition Guidebook
DARPA	Defense Advanced Research Project Agency
DAU	Defense Acquisition University
DCDR	Digital design from Critical Design Review (CDR)
DE	Digital Engineering
DEWG	Digital Engineering Working Group
DL	Descriptive Logic
DoD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DoE	Design of Experiments
DSL	Domain Specific Languages
DSM	Domain Specific Modeling
DSML	Domain Specific Modeling Language
E/DRAP	Engineering Data Requirements Agreement Plan
ERS	Engineered Resilient Systems
FAA	Federal Aviation Administration

FMEA	Failure Modes and Effects Analysis
FMI	Functional Mockup Interface
FMU	Functional Mockup Unit
GAO	Government Accounting Office
GFI	Government Furnished Information
HPC	High Performance Computing
HPCM	High Performance Computing Modernization
HW	Hardware
I&I	Integration and Interoperability
IBM	International Business Machines
IBD	SysML Internal Block Diagram
ICD	Interface Control Document
ICTB	Integrated Capability Technical Baseline
IDEF0	Icam DEFinition for Function Modeling
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
IPR	Integration Problem Report
IRL	Integration Readiness Level
ISEF	Integrated System Engineering Framework developed by Army's TARDEC
ISO	International Organization for Standardization
IT	Information Technology
IWC	Integrated Warfighter Capability
JCIDS	Joint Capabilities Integration and Development System
JEO	Jupiter Europa Orbiter project at NASA/JPL
JSF	Joint Strike Fighter
JPL	Jet Propulsion Laboratory of NASA
KPP	Key Performance Parameter
KSA	Key System Attributes
Linux	An operating system created by Linus Torvalds
LOC	Lines of Code
M&S	Modeling and Simulation
MARTE	Modeling and Analysis of Real Time Embedded systems
MATRIXx	Product family for model-based control system design produced by National Instruments; Similar to Simulink
MBEE	Model-based Engineering Environment
MBSE	Model-based System Engineering
MBT	Model Based Testing
MC/DC	Modified Condition/Decision
MCE	Model-centric engineering
MDA®	Model Driven Architecture®
MDAO	Multidisciplinary Design, Analysis and Optimization
MDD™	Model Driven Development
MDE	Model Driven Engineering
MDSD	Model Driven Software Development
MDSE	Model Driven Software Engineering
MIC	Model Integrated Computing
MMM	Modeling Maturity Model
MoDAF	United Kingdom Ministry of Defence Architectural Framework
MOE	Measure of Effectiveness

MOF	Meta Object Facility
MOP	Measure of Performance
MVS	Multiple Virtual Storage
NASA	National Aeronautics and Space Administration
NAVAIR	U.S. Navy Naval Air Systems Command
NAVSEA	U.S. Naval Sea Systems Command
NDA	Non-disclosure Agreement
NDIA	National Defense Industrial Association
NEAR	Naval Enterprise Architecture Repository
NPS	Naval Postgraduate School
OCL	Object Constraint Language
ODASD(SE)	Office of Deputy Assistant Secretary of Defense for Systems Engineering
OMG	Object Management Group
OO	Object oriented
OSD	Office of the Secretary of Defense
OSLC	Open Services for Lifecycle Collaboration
OV1	Operational View 1 – type of DoDAF diagram
OWL	Web Ontology Language
PDM	Product Data Management
PDR	Preliminary Design Review
PES	Physical Exchange Specification
PIA	Proprietary Information Agreement
PIM	Platform Independent Model
PLM	Product Lifecycle Management
POR	Program of Record
PRR	Production Readiness Review
PSM	Platform Specific Model
QMU	Quantification of Margins and Uncertainty
RT	Research Task
RFI	Request for Information
RFP	Request for Proposal
ROI	Return On Investment
SAVI	System Architecture Virtual Integration
SE	System Engineering
SERC	Systems Engineering Research Center
SETR	System Engineering Technical Review
Simulink/Stateflow	Product family for model-based control system produced by The Mathworks
SCR	Software Cost Reduction
SDD	Software Design Document
SE	System Engineering
SET	Systems Engineering Transformation (as defined by NAVAIR)
SFR	System Functional Review
SLOC	Software Lines of Code
SME	Subject Matter Expert
SOAP	A protocol for exchanging XML-based messages – originally stood for Simple Object Access Protocol
SoS	System of Systems
SOW	Statement of Work
SRR	System Requirements Review

SRS	Software Requirement Specification
STOVL	Short takeoff and vertical landing
SVR	System Verification Review
SW	Software
SysML	System Modeling Language
TARDEC	US Army Tank Automotive Research
TBD	To Be Determined
TRL	Technology Readiness Level
TRR	Test Readiness Review
UML	Unified Modeling Language
XMI	XML Metadata Interchange
XML	eXtensible Markup Language
US	United States
XSLT	eXtensible Stylesheet Language family (XSL) Transformation
xUML	Executable UML
Unix	An operating system with trademark held by the Open Group
UQ	Uncertainty Quantification
VHDL	Verilog Hardware Description Language
V&V	Verification and Validation
VxWorks	Operating system designed for embedded systems and owned by WindRiver

15 TRADEMARKS

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